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Testing and Fabrication of Wire-Bond Electrical Connections— A Comprehensive Survey

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The fabrication and testing of wire-bond electrical connections used in integrated circuits, hybrid circuits, and low-power discrete semiconductor devices are surveyed comprehensively. The survey is generally restricted to wire-bond electrical connections where the wire diameter is less than 2 mils and where the wire is bonded either by thermocompressive or ultrasonic means. Under the general heading of fabrication, the essential features of the thermocompression and ultrasonic bonding processes, the fabrication procedures, and the characteristics of the constituent materials of the wire bond pertinent to high reliability are surveyed. Also included is a review of the interaction of gold and aluminum as one of the primary failure mechanisms in wire bonds. Both new and old test methods are surveyed with emphasis on their capabilities and limitations. In particular, the following test methods are discussed: visual inspection; pull, shear, air blast, push, ultrasonic stress, centrifuge, mechanical shock, variable frequency vibration, vibration fatigue, short-duration stress pulse, temperature cycling, thermal shock, bond interface resistance, and electrical continuity tests; noise measurement; and ultrasonic bond monitoring. Analyses of some of the methods with regard to the stress that the test imposes on the wire bond have been made and the results are used in discussing the relevant methods.

Key words (continued): microelectronics; reliability; survey (wire bond); semiconductor devices; testing (wire bond); thermocompression bonding; ultrasonic bonding; wire bond.

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Bonding; degradation (wire bond); discrete devices; electrical interconnection; fabrication (wire bond); failure (wire bond); hybrid circuits; integrated circuits; (cont.)

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Page 71, Line 10 should read:

pull strength on pull rates in the range of 1 to 77 gf/s for wire bonds with

Page 71, Lines 13, 14, and 15 should read:

equivalent to pull rates, along the wire, of 0.01 to 0.77 mm/min which are much lower than those used by Riben *et al.* The higher pull rate of 0.77 mm/min may be comparable with the speed of some pull test

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Testing and Fabrication of Wire-Bond Electrical Connections - A Comprehensive Survey

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NOTATION*

d	- horizontal bond separation: the horizontal distance between the two bonds of a wire bond. When used, the subscripts o and 1 denote an initial and an altered value, respectively.
E	- modulus of elasticity (Young's modulus).
F	- pull force applied by the pulling probe in a pull test or the pull strength of the wire bond.
F_w	- tensile force in a wire.
F_{wd}, F_{wt}	- tensile force in the wire on the die and on the terminal side of the wire bond, respectively.
$\Delta F(d)$, $\Delta F(t)$	- ratio of the difference in the pull strength produced by changes in the geometric parameters of the pull test from some initial set of values, to the initial pull strength for wire rupture on the die and terminal sides, respectively.
g	- acceleration of gravity.
G	- centrifugal acceleration (in units of gravity).
h	- height of the apex of the wire loop above the terminal bonding surface. When used, the subscripts o and 1 denote an initial and an altered value, respectively.
H	- height difference between the die and the terminal bonding surfaces. When used, the subscripts o and 1 denote an initial and an altered value, respectively.
k	- ratio of the bending to the torsional stiffness (see footnote † on page 106).
T_o , T	- initial and final ambient temperatures, respectively.
α	- ratio of the horizontal distance from the bond on the terminal to where the wire is pulled in a pull test, to the distance d. When used, the subscripts o and 1 denote an initial and an altered value, respectively.
β_w, β_s	- thermal coefficients of linear expansion of the wire and the bonding surface material, respectively.
θ_d, θ_t	- contact angles: angles that the wire makes with the bonding surfaces of the die and terminal, respectively.
ρ	- wire density.
ϕ	- angle from the normal to the bonding surfaces and in the plane which includes the two bonds, that the probe is pulled in the pull test.
ψ_o, ψ	- initial and final contact angles that the wire makes with the bonding surface for a single-level wire bond, respectively, for a change in the ambient temperature.

*Notations are not included where their definition and use are on the same page or in the same table.

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TESTING AND FABRICATION OF WIRE-BOND ELECTRICAL CONNECTIONS — A COMPREHENSIVE SURVEY

Harry A. Schafft

Abstract

The fabrication and testing of wire-bond electrical connections used in integrated circuits, hybrid circuits, and low-power discrete semiconductor devices are surveyed comprehensively. The survey is generally restricted to wire-bond electrical connections where the wire diameter is less than 2 mils and where the wire is bonded either by thermocompressive or ultrasonic means. Under the general heading of fabrication, the essential features of the thermocompression and ultrasonic bonding processes, the fabrication procedures, and the characteristics of the constituent materials of the wire bond pertinent to high reliability are surveyed. Also included is a review of the interaction of gold and aluminum as one of the primary failure mechanisms in wire bonds. Both new and old test methods are surveyed with emphasis on their capabilities and limitations. In particular, the following test methods are discussed: visual inspection; pull, shear, air blast, push, ultrasonic stress, centrifuge, mechanical shock, variable frequency vibration, vibration fatigue, short-duration stress pulse, temperature cycling, thermal shock, bond interface resistance, and electrical continuity tests; noise measurement; and ultrasonic bond monitoring. Analyses of some of the methods with regard to the stress that the test imposes on the wire bond have been made and the results are used in discussing the relevant methods.

Key Words: Bonding; degradation (wire bond); discrete devices; electrical interconnection; fabrication (wire bond); failure (wire bond); hybrid circuits; integrated circuits; microelectronics; reliability; survey (wire bond); semiconductor devices; testing (wire bond); thermocompression bonding; ultrasonic bonding; wire bond.

1. INTRODUCTION

wire bonds† (importance of)

The use of wire is still the predominant way of electrically connecting the semiconductor dice and package terminals in integrated circuits, hybrid circuits, and low-power discrete semiconductor devices.* The wire used is typically 1 mil in diameter and may be as small as 0.7 mil. The reliability of most of these devices is very high, but because of the large number of devices used in many present-day high-reliability systems, maintaining and increasing the component reliability remains a function of critical importance. Because a significant fraction of the failures that do occur are failures of the electrical connection [65B2], [68C1], [68S2], [69H2], [69L1], [69O1], [70M3], the improvement and testing of these connections is a major concern.

reliability

wire bond components

The term wire bond is used in this paper to refer to all the components of this wire electrical connection. These components are illustrated in a sketch of a thermocompression ball-stitch wire bond in figure 1; they are the wire, the metal bonding surfaces, and the adjacent underlying supportive material. Each one of the elements indicated in the figure is a possible failure point of the wire bond.

reliability improvement

Most wire bonds do not fail. The problem is not that the technology is unavailable to make highly reliable wire bonds. It is. Rather, the problem is the inability to make the same wire bond every time and, the corollary, the inability to identify sufficiently early those which will eventually fail during subsequent tests, in handling, or in use. Simply put, the two critical areas for reliability improvement of wire bonds are the control of the manufacturing processes and the methods for testing and evaluating wire bonds.

purpose

The purpose of this paper§ is to evaluate and review these two critical areas for wire bonds with wire diameters less than 2 mils. Consequently there

*Other connecting methods such as spider bonding, beam leads and other face-down schemes are in growing use. Although setup costs are large, these all offer the advantage of being able to make many bonds simultaneously. The more efficient bonding process and the reduction in the human element in production offer the potential for lower cost and greater reliability. Nevertheless, the vast experience with wire connections plus the inherent flexibility of their use will continue to make this method important for some time in the future, in the opinion of many experts [68P1], [71B2], [71J1], [71M1]. Uthe [71U1] has suggested that the use of wire bonds is, in fact, increasing. He reported that as a result of the economic reversals in 1970-1971 many equipment engineering groups have been disbanded. As business begins to increase most companies no longer have the engineering talent and capability to implement the newer interconnecting methods. Thus, the problem of achieving higher reliability for wire bonds will continue to be of great significance. This is especially so for space and military applications where extremely reliable devices are often required in relatively small production lots that do not lend themselves to the use of multi-bonding schemes.

†Key words or phrases are placed in the margins to assist in scanning.

§This survey constitutes a portion of work on wire-bond evaluation which is being supported by the National Bureau of Standards, the Defense Nuclear Agency, and the U. S. Navy Strategic Systems Project Office (NAD, Crane) and is being performed at the National Bureau of Standards as part of a comprehensive program on methods of measurement for semiconductor materials, process control, and devices. Work in this program is reported in quarterly reports and published as NBS Technical Notes [72B3].

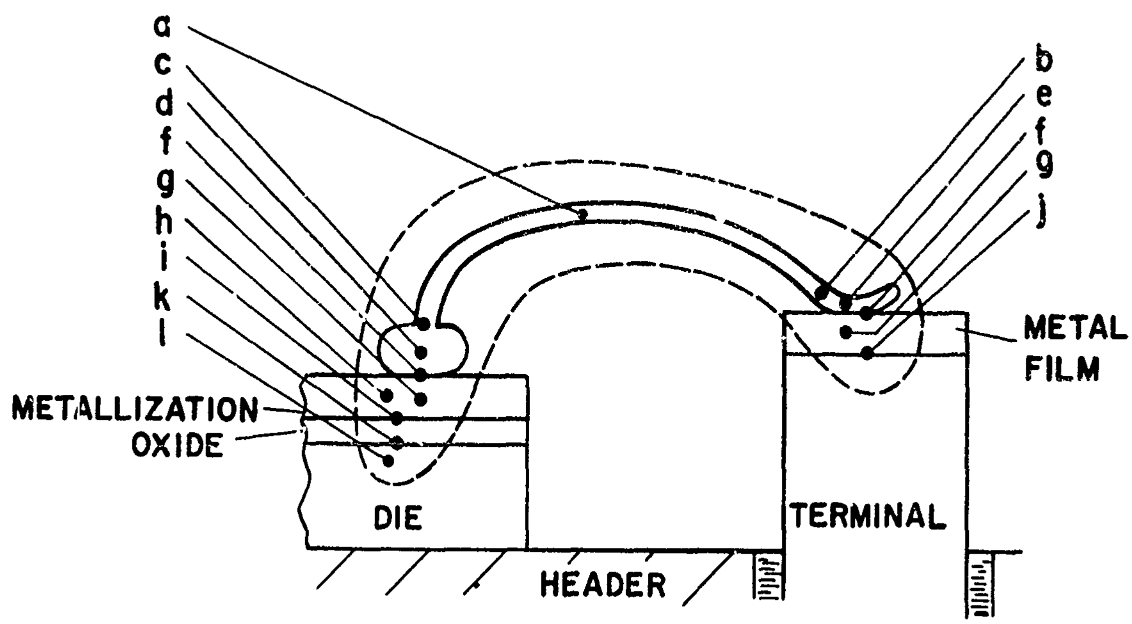

Figure 1. Sketch of a thermocompression ball-stitch wire bond (enclosed by the dashed line) with the various elements of the wire bond indicated where failure can occur. The elements identified are as follows:

a. Wire.
b. Heel of the bond.
c. Wire emerging out of the top of the wire material melted to form a ball prior to being deformed in the process of making the ball bond.
d. Wire material melted to form a ball and deformed in the process of making the ball bond.
e. Wire material deformed in the process of making the bond and located over the bond between the wire and bonding surface.
f. Bond interface between the wire and the bonding surface.
g. Metal-film bonding surface. It may be multilayered.
h. Metal film (metallization) at the perimeter of the bond interface.
i. Interface between the metal-film bonding surface and an underlying insulating layer, usually a silicon oxide.
j. Interface between the metal-film bonding surface and the terminal.
k. Interface between the insulating layer and the silicon substrate.
l. Silicon substrate.

are two major sections to the paper. Section 4 addresses the fabrication of wire bonds with emphasis on controlling the procedures and processes, and section 5 addresses both new and old test methods with emphasis on their capabilities and limitations. The various failure mechanisms and failure modes are discussed in the context of fabrication and testing in the appropriate sections.

approach

glossary

self consistency

subject index

references

The paper has been written in a way which is intended to be useful both to the relative novice and to those more experienced in wire-bond technology. A glossary of terms used in the paper is provided primarily for the former who may wish to proceed in order through the text. Separate sections of the paper are written in as self consistent a manner as possible to permit the more experienced worker to read only those sections of interest to him. To further assist the reader, a subject index is provided and each literature citation in the list of references is followed by the page number(s) where the document is cited in the text.

information sources

Information included in this paper was obtained from the published literature; from unrestricted government reports;* and from interviews with engineers in government laboratories and in the development and production facilities of semiconductor device, bonding machine, and bonding tool manufacturing companies.

dearth of information

Review of the literature and the information obtained in personal visits leads to the conclusion that there is a dearth of well documented experimental work and a proliferation of hearsay and conclusions based on data from experiments where the test methods, the wire bonds tested, and the fabrication procedures have been incompletely specified. The survey paper reflects this paucity of definitive information. Incomplete information about optimum bonding conditions and procedures abounds with regard to the condition of the bonding surface, the wire material used, the bonding tool design, and the control required of the bonding parameters. A similar situation exists for methods used to evaluate wire bonds. All methods use one or more criteria to judge the quality of the wire bond, but the relation of these criteria to the anticipated stresses and the potential reliability of the wire bond is at best uncertain; test variables have not been explored sufficiently to determine their effect on the value of the measure used; and, usually the methods are underspecified and the wire bond tested is insufficiently described.

compensation for uncertainties

In an attempt to compensate for the uncertainties in the stressed imposed by the test and their relation to those stresses that the wire bond will need to sustain in use, recourse is taken to making wire bonds as strong and as uniformly the same as possible and to testing to stress levels greater than

*Some cleared information from limited distribution documents is included and referenced as private communications.

would appear necessary. For example, the centrifuge test is recommended by many for testing wire bonds with gold wire but not for testing those with aluminum wire; the stress imposed on the aluminum wire is significantly less for the same acceleration level because of its lower density. But if the reliability of the wire bond were primarily affected by a centrifugal stress the method should be satisfactory for both wire materials.

A comprehensive bibliography on wire bonds by the author [72S1], which includes a detailed key word index, is a recommended companion paper to this survey.

bibliography

2. GLOSSARY

ball bond	— Bond formed with a capillary-type tool when the end of the wire has first been formed into the shape of a ball (by melting the wire with, for example, a flame as in a flame-off procedure). Also referred to as a nail-head bond. See figure 3.
bond	— The part of the wire bond that is associated with the volume of wire deformed at an attachment point.
bond deformation	— The change in the dimensions of the wire at an attachment point produced by the bonding tool in making the bond. The deformation is usually measured in units of wire diameter.
bonding area	— The area within which the wire is to be attached to a terminal or die.
bonding schedule	— The values of the bonding variables used in bonding. For example; in ultrasonic bonding, the values of the bonding force, time, and ultrasonic power.
bonding surface	— The metallic surface or film to which the wire is or is to be interfaced and bonded.
bond lift-off	— The failure mode where the bonded wire separates from the bonding surface.
bond separation	— The distance between the attachment points of the first and second bonds of a wire bond.
capillary tool	— A tool such that the wire is fed to the bonding surface of the tool thru a bore located along the long axis of the tool.
direct contact	— A contact such that the wire is bonded directly over the part of the semiconductor die to be electrically connected, as opposed to an expanded contact. See figure 2.
elongation	— The ratio of the increase in wire length at rupture in a tensile test to the initial wire length, given in percent.
expanded contact	— A contact such that the wire is bonded to an area remote from the part of the semiconductor die to be electrically connected so that a lateral interconnection path for the current is required. See figure 2.
eyelet tool	— A special wedge-type bonding tool designed to maximize the movement of the wire surface in contact with the bonding surface while the wire is deformed during the making of the bond. See figure 4.
first bond	— The first bond in a sequence of two or more bonds made to form a wire bond.
flame-off	— The procedure where the wire is severed by passing a flame across the wire thereby melting it as in gold-wire thermocompression bonding to form a gold ball for making a ball bond. See figure 3.
flying-lead bond	— See wire bond.
foot length	— The long dimension of the bonding surface of a wedge-type bonding tool. See figure 12.
gram-force	— A unit of force (nominally 9.8 mN) required to support a mass of one gram (1 gravity unit of acceleration × 1 gram of mass = 1 gram-force). Colloquially, the term *gram* is used for the unit.

heel (of the bond) — The part of the wire that has been deformed by the heel of a wedge tool used in making the bond (see figure 12). The term is used primarily with reference to ultrasonic wedge bonds.

Kirkendall effect — The formation of voids, by diffusion across an interface between two materials, in the material having the greater diffusion rate into the other.

Kirkendall voids — Voids formed by the Kirkendall effect.

lift-off — See bond lift-off.

loop (wire) — The curve formed by the wire between the attachment points at each end of the wire.

loop height — A measure of the deviation of the wire loop from the straight line between the attachment points of a wire bond. Usually, it is the maximum perpendicular distance from this line to the wire loop.

metallization — The metal film (single or multilayered) on the semiconductor die used to connect electrically different areas on the die.

overbonding — Excessively deforming the wire, with the bonding tool, during the bonding process.

package — The container for the semiconductor die or dice with terminals to provide electrical access to the inside of the container.

pad, bonding — Bonding area on the semiconductor die.

peel, bond — Similar to lift-off of the bond with the idea that the separation of the wire from the bonding surface proceeds along the interface rather than occurring all at once.

plastic device — A device where the package or the encapsulant for the semiconductor die is made of such materials as epoxies, phenolics, silicones, etc.

post — See terminal.

Q — The ratio of the resonant frequency of the oscillating system to the frequency band between half-power points (band width). In the present context, Q refers to the Q of the electro-mechanical system of an ultrasonic bonder, in particular to the sensitivity of the mechanical resonance to changes in driving frequency.

search height — The height of the bonding tool above the bonding area, at which final adjustment in the location of the bonding area under the tool is made prior to lowering the tool for bonding.

second bond — The second bond in a sequence of bonds made to form a wire bond.

stitch bond — A bond made with a capillary-type bonding tool when the wire is not formed into a ball prior to bonding.

tail (of the bond) — The free end of wire extending from the point where the wire is attached to the bonding surface.

tensile strength — The force required to rupture a wire under tensile load.

terminal — A metal element used to provide electrical access to the inside of the device package.

thermocompression bonding	— A process involving the use of pressure and temperature (not high enough to cause melting) to join two materials.
tool, bonding	— An instrument used to press the wire against the bonding surface in the making of a bond.
ultrasonic bonding	— A process involving the use of ultrasonic energy and pressure to join two materials.
underbonding	— Insufficiently deforming the wire, with the bonding tool, during the bonding process.
wedge bond	— A bond made with a wedge tool. The term is usually used to differentiate thermocompression wedge bonds from ball and stitch bonds. (Almost all ultrasonic bonds are wedge bonds.)
wedge tool	— A bonding tool in the general form of a wedge with or without a wire-guide hole to position the wire under the bonding face of the tool, as opposed to a capillary-type tool.
wire	— Unless otherwise specified, wire with a circular cross-section with a diameter less than 2 mils, and with either gold or aluminum as the principal constituent material.
wire bond	— All the components of a wire electrical connection such as between the terminal and the semiconductor die. These components are the wire, the bonding surfaces, and the underlying supportive material. See figure 1.

3. WORD ABOUT UNITS

Most of the data referenced in this paper that are not given in the International System of units are followed in parentheses by the values in the appropriate International System unit. General usage had dictated that three exceptions to be made: (1) acceleration is given in units of gravity, g (1 g = 9.8 m/s^2), (2) the wire diameter is given in mils (1 mil = 25.4 μm), and (3) the force exerted on the wire or wire bond is given in grams-force (1 gf = 9.8 mN). With respect to the last unit, common usage is not even to use the term grams-force but simply grams. In the interest of the proper usage of units, the unit grams-force is used even though the data may have been given in *grams*.

4. FABRICATION OF WIRE BONDS

fabrication of wire bonds

4.1. Introduction

Thermocompression and ultrasonic bonding are two principal processes used in microelectronics to bond wire to metal surfaces on semiconductor dice and on terminals. The essential features of the bonding process and fabrication procedures pertinent to high reliability are discussed separately according to bonding process. Preceding this is a discussion, in the context of bonding and wire-bond reliability, of the wire and metal bonding surfaces commonly used. Following this discussion is a review of one of the primary wire-bond failure mechanisms, gold-aluminum interactions (intermetallic compound formation and Kirkendall voids).

wire

4.2 Wire

Wires are usually made of either gold or aluminum. Gold wire is most often used in thermocompression bonding while aluminum wire is most often used in ultrasonic bonding. Wire hardened to some degree is needed to ease handling and aligning the fine wire while fabricating wire bonds. Gold tends to age to its amorphous state with a consequent decrease in tensile strength. Because hard-drawn gold wire ages significantly at room temperature, the softer and relatively more stable stress-relieved wire is recommended [64C1]. Pure aluminum cannot be hardened sufficiently to allow it to be drawn to a diameter of 1 mil [69P1], [6902]. Therefore, aluminum is usually hardened by adding about one percent of an impurity such as silicon or, less frequently, magnesium.

Au

Al

wire drawing

Techniques other than those for standard wire drawing are being developed to form small diameter wires. One is a continuous hydrostatic extrusion process [70S1]. Another is a process for drawing copper-cladded aluminum wire [6902]; the copper is etched away after drawing to the desired size. While pure aluminum may be drawn in these ways it may not be sufficiently hard to be handled conveniently.

characteristics (measurement)

A number of methods are available for measuring the different characteristics of the wire. ASTM standard methods are available for measuring wire dimensions [70A4], [70A5], tensile strength [70A6], and resistivity [70A7]. A technique which permits the automatic recording of load-strain curves has been recently described by Hart [71H3] although at least one commercial tensile testing machine already incorporates such a feature. In an effort to determine the hardness uniformity of the wire in terms of some deformation measure more closely related to bonding conditions, the use of a wedge to be applied with a given force along sections of the wire has been considered

[71R4].* With the high intensity available from a laser it has become possible to use simple diffraction effects to measure continuously, with 1/2 percent accuracy, the wire radius as it is drawn [66K2], [69G3]. Because the intensity of the diffraction pattern is also a function of the reflectivity of the surface the method can be used to monitor the condition of the wire surface.

standards

An ASTM Standard specification for gold wire is available [70A3] but not for aluminum wire. This is not because the specifications of gold wire are more important or critical, rather it is due to the fact that gold wire was first used extensively. The ultrasonic bonding technology for using aluminum wire lagged initially. Also, the problems with specifying aluminum wire are more complex, as will be discussed later, and this too has hindered standardization. A standard specification for hardened aluminum wire is needed to define the pertinent wire characteristics, and how to measure them, so that wire of a consistent bonding quality may be produced, purchased, and used.

wire specifications

The three most often specified wire parameters when ordering or describing wire are the diameter, tensile strength, and elongation. It is important to have wire of a constant and known cross sectional dimension because the bonding conditions, to be discussed later, depend on the mass of wire involved in making both thermocompression and ultrasonic bonds.

for TC bonding

The specification of the tensile strength and elongation is somewhat less important for gold wire in thermocompression bonding than for aluminum wire in ultrasonic bonding. For thermocompression bonding, changes introduced during the pre-heating and the heating during bonding are probably more important than the initial condition of the gold wire.

for US bonding

For ultrasonic bonding with aluminum wire, a low elongation is required so that the wire may be broken after the second bond of the wire bond is made without undue distortion of the adjacent wire which will be used in the first bond of the next wire bond.

elongation

If the elongation is too large, such distortions may be sufficient to cause the next bond to be inferior. Too great an elongation may also result in an excessively long tail in the second bond. The elongation that is usually specified is from 1 to 2 percent. Ravi and Philofsky [71R1] have pointed out that the measured elongation of aluminum wire depends on the strain rate and gage length. Thus when specifying an elongation specification the method of test is important.

tensile strength

Relatively hard wire is needed to minimize deformation of the wire during ultrasonic bonding of small diameter (< 2 mil) wire. The range of tensile strength used is from about 12 to 20 grams-force. Cox *et al.* [70C1]

*Also S. Bonis and T. Salser, Raytheon Co., Sudbury, Mass. 01776; private communication.

recommend a range of 14 to 16 grams-force, saying that use of a higher tensile strength (or harder) wire may fracture the silicon under the bond to the die. The use of lower tensile strength (or softer) wire reduced the range of the bonding schedules for which satisfactory bonds may be achieved. Also, the softer wire is more difficult to handle and align under the bonding tool.

handling

Care in handling the fine wire and protecting it from stress in all steps before bonding is important [67B2], [70A3]. Wire is wound in a single layer on the spool to avoid binding and to aid in visual inspection of the wire. Dropping the spool may dislodge the wire and interfere with free despooling of the wire and the distortion due to the tensile stress on the wire in despooling can result in inferior wire bonds [68S1]. It is important to avoid extremes in temperature to which the spooled wire is exposed, such as in transport, because the difference in the thermal expansion coefficient of the wire and spool may result in undue tensile stress or shifts of wire location [64C1].

contamination

It is vitally important that the wire be free of surface contamination. A serious potential contamination problem is the insufficient removal of the lubricating material used in drawing the wire. These lubricants are essentially transparent, and film residues a few hundredths of a micrometer thick on the wire are difficult to detect by optical or other means. In addition to the possiblity of interferring with making the bond, their presence can lead to problems such as corrosion of aluminum metallization [71L1] or later device degradation due to the water or ionic contaminants that may be included with the lubricant. All wire cleaning must be done by the manufacturer because the wire can neither be properly cleaned on the spool nor be respooled.

degradation

Devaney [70D1] has shown striking SEM photos of wire bonds made with gold wire contaminated with wire lubricants and with human contact. Scarbrough and Auchterlonie [67S2] presented an example of how the transistor gain can be degraded by organic residues of the lubricant on the aluminum wire used. They postulated the possibility that some of the lubricant was trapped below the surface of the wire during drawing. The problems that alkali residues on magnesium-doped aluminum wire have caused will be discussed later in this section.

Al + 1% Si wire

problems

The addition of 1 percent silicon to harden aluminum for drawing and bonding has resulted in numerous problems. These problems occur as a result of the very low solubility of silicon in aluminum at room temperatures [67V1]. The instability of this metallurgical system leads to an annealing of the wire in time, even at room temperature [69J1]. Hence such wire is considered to have a limited shelf-life because the ease of handling and the adjustment of the bonding variables depend on the hardness of the wire. In extreme cases, silicon precipitates in localized regions causing gross non-uniformity

in the hardness of the wire. When bonding with such wire, silicon precipitates may cause a fracture in the silicon under the bond of the die. Grain growth can occur during exposure to the high temperatures (∿ 500°C) employed in sealing some ceramic packages. These grains can span the wire and severely reduce the ability of the wire to withstand mechanical stress [66K1], [69P1], and [71R1]. Also, the rate of cooling from 500°C, where one percent of silicon is soluble in aluminum, can affect the amount of silicon precipitated; the slower the cooling rate, the greater the precipitation.

A number of studies have been made of the mechanical and physical properties of commercially available aluminum wire with 1 percent silicon and the dependence of these properties on temperature and time [70C1], [70P1], [71R1]. Large differences in the size and distribution of the silicon precipitates in the aluminum wire as received from the manufacturer have been reported [70C1], [71R1]. Ravi and Philofsky [71R1] found that the most striking effect of these differences was upon the ductility of the wire. A maximum in the ductility was observed at a strain rate of 10^{-4} s^{-1} for a uniform distribution of silicon particles in the tens-of-nanometers size range. In wire with larger sized silicon particles, but still smaller than 2 μm in extent, this maximum in ductility was not observed. The ductility and the tensile strength was not otherwise changed by the increase in particle size. However, for wire with silicon particles larger than about 2 μm the tensile strength was reduced. Cox *et al.* [70C1] found significant differences in the distribution and size of silicon in wires produced by different manufacturers to the same specifications. All aluminum wires with silicon exhibit a reduction in tensile strength and elongation with exposure to elevated temperatures as the silicon precipitates grow in size. Any initial differences between wires become small after such aging, therefore high tensile strength wires show the more pronounced reductions. For example, the wire data from Prankatz and Collins [70P1] shows about a 50 percent reduction in an initial tensile strength of about 20 grams-force after about 100 hours storage at 150°C, or after about 1 hour storage at 200°C. Fully annealed wire was obtained after one hour storage at 300°C.

Si precipitates

ductility

tensile strength

effect of temperature

The use of wire in which the silicon is uniformly distributed with individual silicon particles too small to be seen with a scanning electron microscope at a magnification of 3000 X has been recommended by Cox *et al.* [70C1]. This recommendation and a similar one by Ravi and Philofsky [71R1] are not based on any reliability data; rather, they are based more on an intuitive feeling for what the optimum conditions of silicon dispersion should be. It is to be expected that the more finely dispersed the silicon is, the longer it should take before significant precipitation occurs.

Si particle size

bonding schedule

Of significance to bonding with wires having different mechanical properties is the observation of Cox *et al.* [70C1] that such differences affect the bonding process. Thus if a different wire is used, a change in the bonding schedule may be required. They also found that wire bonds made with a higher tensile strength wire were less sensitive to changes in the bonding schedule than those made with a lower tensile strength wire. The example they documented, however, compared a harder wire with silicon inclusions to a softer wire with no silicon inclusions.* It would be interesting to compare the results using wires with the same tensile strength and different sized silicon particles to evaluate better their recommendation for using wire with no "visible" inclusions.

stabilized wire

Recently wire manufacturers have introduced a stabilized silicon-hardened aluminum wire by adding a third element such as titanium to produce a ternary alloy which is thermodynamically stable over the temperature range of interest. A simpler alternative has been available. Magnesium has been substituted for silicon to harden the aluminum wire. A 1 percent solid solution of magnesium in aluminum is stable at room temperatures [67V1]. Such wire appears to have essentially the same mechanical and bonding characteristics as aluminum wire with 1 percent silicon [69U1], [69P1], [70P1] with the added advantage that the wire exhibits superior fatigue characteristics† [72R1] and its tensile strength is less affected by exposure to high temperature [70P1]. However, Plough *et al.* [69P1] and Davis [70D2] found that the presence of aluminum wire with 1 percent magnesium caused transistor gain degradation after high temperature storage. Uthe [69U1] implied the existence of such a problem. These reports served to bring to the surface suspicions about the use of this wire that others had expressed privately. However Pankratz and Collins [70P1] have questioned the basis of these suspicions. Their studies showed that devices bonded with aluminum wire with 1 percent silicon *degraded no less* with high temperature storage than those bonded with aluminum wire with 1 percent magnesium. More recently in a continuation of work reported by Plough *et al.* [69P1], evidence was uncovered to show that the earlier reported device degradation while using aluminum wire with 1 percent magnesium resulted from using wire with an alkali-containing wire lubricant residue. When an alkali-free wire-lubricant was used no such degradation was observed.§ This development gives added support to renewed consideration of the use of aluminum wire with 1 percent magnesium.

Al + 1% Mg wire

*The two wires had slightly different diameters. The tensile strengths, normalized to 1 mil diameter wire, were 17.3 gf and 15.5 gf, respectively.

†An important consideration for devices to be subjected to a large number of on-off power cycles (see section 5.13.2).

§H. L. Floyd, Jr., Sandia Corp., Albuquerque, New Mexico 87115, private communication.

Kessler [69B5] has suggested the use of ribbon wire for making ultrasonic bonds instead of round wire. Preliminary work with ribbon wire with essentially the same cross-sectional area as 1 mil diameter wire (1.5 · 0.5 mils) has shown that less pressure is required to make the bond. Thus, the bond has a smaller deformation and the bond area is no greater than the area needed for round wire. In addition to the advantages of greater ease in handling and aligning, the use of ribbon wire offers the opportunity of strengthening the normally weakest part of wire bond, the heel of the first bond. Because less pressure is required, higher tensile strength wire can be used without fracturing the silicon when bonding to the die. The resulting decrease in the necessary deformation appears to strengthen significantly the heel of the first bond [72B2]. Work in evaluating the advantages of using ribbon wire has indicated that the control of the bonding schedule is less critical for ribbon wire than for round wire, as judged from the results of pull tests [72B1].

ribbon wire

4.3. Bonding Surface

metal film (die)

The metal film most used on the semiconductor die is aluminum. When gold is used, it is to avoid problems associated with the formation of gold-aluminum intermetallic compounds. Because gold does not adhere well to silicon dioxide and direct contact of gold to silicon is to be avoided,* other metals must be incorporated to form a multilayer metallization system.

Al vs. multilayer system

Schnable and Keen [69S2] have described extensively the advantages and limitations of using aluminum metallization and concluded that it offers significant advantages over any other single or multilayer metallization system that has been considered for integrated circuit applications. They agreed with Selikson [69S3] that multilayer metallization systems suffer in comparison not so much from inherent material limitations, but rather from fabrication complexity where high fabrication costs and potentially lower yield are the problems.† Cunningham and Harper [67C1] in an earlier paper presented arguments for the use of a gold-molybdenum metallization system over the use of a pure aluminum metallization. Their arguments were based primarily on the greater metallurgical stability of the former when gold wire is used in the wire bond. They however did not speak to the fabrication-related problems associated with the greater complexity of the system.

*Gold diffuses rapidly in silicon at high temperatures that are encountered in such procedures as thermocompression bonding, the sealing of some ceramic packages, and high temperature storage. The presence of gold reduces the minority carrier lifetime in silicon which can lead to degradation of the electrical characteristics of the device.

†Problems of poor adhesion and the use of the shear test to detect them are discussed by Gill and Workman [67G1].

metal film (terminal)

Au

Au-plating specification

Al

The base metal of the terminal is usually an iron-nickel-cobalt (FeNiCo) alloy [70A8], designed to be thermally compatible with the glass seal used in many device packages. The terminal, as part of the package supplied to the semiconductor device manufacturer, is plated with gold, in most cases. Even though the usage of gold plating is very common, the methods for specifying and measuring the plating with respect to such properties as purity, organic co-deposits, thickness, roughness, hardness, and porosity, are still inadequate, as has been discussed by Antler [69A3], because too little is understood about the properties of gold platings and how to measure them. To avoid gold-aluminum interactions on the terminal when aluminum wire is used, the terminal may be covered with aluminum. In rare cases, the terminal is bare and aluminum wire is bonded directed to the alloy.

factors affecting bonding

Bonding to the die and the terminal can be affected by many film-related factors: surface smoothness, film hardness and thickness, film preparation, and surface contamination, to name a few, but bonding technology is still not developed to the point where any consensus exists about the optimum film conditions for fabricating a given type of wire. Only a little of this kind of information exists in the literature with supporting experimental data. Some of the comments that have been made in the literature and in interviews about factors that may affect bonding wire to metal films are reviewed in the next several paragraphs. Comments relevant to thermocompression bonding are considered first.

TC bonding

Howell and Slemmons [64H2] indicated that for thermocompression bonding, the uniformity, composition, and thickness of the metallization were important and that, in particular, surface irregularities can prevent adequate diffusion across the wire-metallization interface and hence interfere with making a bond (see section 4.5.1). To insure adequate quality of the metallization for bonding they proposed that one or more test areas should be made available for bond pull tests. Hill [64H1] reported that by improving the uniformity of the aluminum metallization thickness it appeared that the reliability of the gold wire thermocompression bonds had been improved, but results were not shown.

TC bonding (thick film)

Budd [69B3] evaluated the use of a representative group of thick-film metallizations for making gold wire thermocompression and aluminum wire ultrasonic bonds. Both the composition and firing conditions of the thick film had an effect on the pull strength of the wire bonds. Goldfarb [71G2] reported that for ultrasonic bonds with aluminum and gold wires to four thick-film gold materials studied, increased firing time tended to result in an increase in the pull strength of the gold wire bonds and a slight decrease in the strength of the aluminum wire bonds. No systematic dependence on the thick-films examined was found.

US bonding (thick film)

Goldfarb also reported severe degradation of aluminum wire ultrasonic bonds to thick-film gold materials with exposure to a sealing temperature cycle which included exposure to temperatures greater than 350°C for 10 minutes. The degradation was indicated by increased electrical resistance of the bond, decreased pull strength, and increased frequency of bond lift-off in pull tests. Although not mentioned, the failure mechanism appears to be the formation of Kirkendall voids beneath the bonds. Thus, it would appear that gold-aluminum interfaces on thick-film conductors are to be avoided if the wire bond is to be exposed to high temperatures.

US bonding

Al sintering temperature

In the case of aluminum metallization, the temperature at which the film is sintered, to achieve adequate adhesion [65R2], appears to have an effect on ultrasonic bonding. Leedy *et al.* [70B3] found a sintering temperature dependence for aluminum wire ultrasonic bonds to 0.5-μm thick aluminum films on oxidized silicon. Pull strengths of wire bonds on films sintered at 500°C and 550°C were statistically similar and greater than those on films sintered at 425°C and at 577°C.

Al hardness

The hardness of the aluminum metallization is said to be important. It should be somewhat softer than the wire so that surface irregularities may be easily smeared out to better conform to the wire [69P1]. Too soft a metallization may cause problems: Davis [70D2] reported that "excessive" thickness results in a soft metallization to which it is difficult to bond. Also, some concern has been expressed that the use of a soft aluminum metallization could result in filaments of aluminum being extruded from under the bonded region during bonding which if subsequently dislodged could cause short-circuits.

Al, Au thickness

The thickness of aluminum or gold metallization can have an effect on bondability and on subsequent reliability. There is generally no difficulty encountered in bonding to films with a thickness within the typical range used (0.7 to 1.2 μm). Inconsistent bonding has been reported on films of thickness less than 0.5 um [67R1]. To avoid subsequent bond failure due to intermetallic compound growth and Kirkendall voids (see next section) at the interface, Philofsky [71P1] suggested that the thickness of the metal film be minimized, consistent with good bonding and device design. This suggestion applied both when bonding gold wire to aluminum on the semiconductor die and when bonding aluminum wire to gold plated terminals. Kashiwabara and Hattori [69K3] found that subsequent failure of aluminum wire bonds to gold plated terminals did not occur at storage temperatures less than 350°C if the width of the wire-film bond interface area was greater than 4 times the thickness of the gold plating. They reported that the width of the actual wire contact was typically about 0.6 of the wire deformation (as viewed from above) for a 3 μm thick gold film and about 0.8 for a 15 μm thick film.

Al, Au thickness

When the device is to be subjected to thermal or power cycling, wire flexing at the heel of the bond will occur. Philofsky [71P1] suggested that under these circumstances the thickness of the aluminum metallization should be less than one-sixth of the wire thickness at the heel of gold-wire wedge or stitch bonds to avoid the growth of brittle intermetallic compounds up into this region and consequent fracture of the wire at the heel of the bond; for the case of aluminum wire bonds to gold-plated terminals he suggested that the thickness of the plating should be less than one-third the wire thickness at the heel of the bond. If either of these design recommendations is not feasible he provided maximum safe exposure times for the wire bonds to elevated temperatures, based on the kinetics of transformation to the intermetallic compunds.

surface roughness

Excessive roughness of the bonding and substrate surfaces has been said to influence the quality of ultrasonic bonds. Considering the constraints on the thickness of the metallization, a substrate roughness of 30 µin. (0.76 µm) was considered highly undesirable and one less than about 3 µin. (0.076 µm) was preferred* [67L1], [67R1]. Davis [70D2] recommended that the bonding surface roughness must be such that the area of the bond be large compared with the peak-to-peak variations in the surface. As an example, he suggested the surface finish be from 4 to 8 µin rms (0.1 to 0.2 µm) for a 1-mil diameter wire and a 1-mil (25 µm) tool foot-length. Johannesen [71J1] mentioned that wire deformation is affected by surface roughness, but the roughness and degree of effect was undefined.

bonding to terminal

Au plating surface

Making bonds of consistent quality to the terminal (usually an iron-nickel-cobalt alloy) is often more difficult to do than making consistent bonds to the die. This is because package technology is far less sophisticated and far less in tune with the needs of wire bonding. This is particularly true for ultrasonic bonding. The finish of the gold plating is often not sufficiently uniform or consistent to allow high quality bonds to be made. Johannesen [71J1] cautioned that from his experience, gold platings that show distinct grain structure or discoloration are unacceptable for bonding. Also, the terminal is often so high that it is insufficiently rigid for ultrasonic bonding† and the bonding surface on the terminal is often insufficiently flat or horizontal. The remedy is to grind down the terminal to the desired height and flatness. The smooth finish thought to be necessary for good bonding may be difficult to achieve when gold plating the ground-down terminal. Generally,

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*In this instance and in some to follow, information was not provided to indicate if these values for roughness are for peak-to-peak, rms, or other measures.

†The terminal height should not be a resonant length with respect to the ultrasonic driving frequency or its harmonics [68U5]. Davis [70D2] has suggested that for sufficient rigidity the terminal height should be no more than one-half to one-third the diameter of the terminal.

large-sized grains of the alloy are exposed on grinding. The pre-plating etch tends to etch preferentially at these grain boundaries and produce a rough surface. Two alternative techniques have been reported that can provide sufficiently smooth, gold-plated finishes.* Both methods eliminate the pre-plating etch step and replace it with a thorough cleaning procedure. In one method the terminals are stone lapped while in the other method the terminals are chemically polished to the desired height.

contamination (surface)

Contamination on the bonding surface should be avoided. For thermocompression bonding, it interferes with intimate contact and interdiffusion of the wire and metal film and contributes to making poorer bonds [64H2], [67K1]. The problem of contamination may be considered to be less for ultrasonic bonding because of the ultrasonic agitation. However, even if the bonding schedule can be adjusted to break thru the barrier, such adjustments generally involve increases in power, time, or force and as such can result in increased deformation at the heel of the bond and hence reduce the pull strength of wire bonds at bonding sites where the barrier is not as severe.† A number of contaminants capable of interfering with bonding have been mentioned in the literature. They are residues of chemicals used in the photoresist [69P1] and package plating operations [72H2], water spots, silicon monoxide, silicon dust (from scribing), and aluminum oxide [66H1]. A radiotracer technique has been used to detect photoresist residues [69H1]. Antle [64A1], [66A1] has indicated the possible usefulness of a friction technique to study the effects of surface contamination and of atmospheric ambients, but the work reported dealt with wire metals not generally used in microelectronics.

contamination (plating bath)

With regard to contamination-induced bond degradation, Horsting [72H2] found that impurities (greater than about the 0.1 percent level) in the gold plating bath used to gold plate nickel-plated, iron-nickel-cobalt terminals could cause bond failures at the terminals after high-temperature storage. In particular, he reported bond failures of aluminum wire, ultrasonic bonds after storage of about 1000 hours at 200°C.

4.4. Gold Aluminum Interactions§

intermetallic compounds

A typical wire bond has a gold-aluminum interface either at the die or at the terminal. Gold-aluminum intermetallic compounds form at this interface at

*H. L. Floyd, Jr., Sandia Corp., Albuquerque, New Mexico 87115, private communication.

†G. G. Harman, National Bureau of Standards, Washington, D. C. 20234, unpublished results.

§For further reading about the subject of gold-aluminum interactions, the paper by Selikson [69S3] serves as a good, recent review. Earlier papers by Cunningham [65C5] and Blech and Sello [66B3] are also recommended. The paper by Philofsky [70P2] provides an informative study of the growth of Kirkendall voids and the different intermetallic compounds with temperature.

temperature

a rate that increases with temperature. Above a temperature between about 125 and 150°C [67C1], [6901], the growth rate becomes significant with respect to long-term reliability of wire bonds. This is within the range of some operating environments, lower than the maximum temperature specified in many storage and thermal cycling tests, much lower than the temperatures at which thermocompression, and perhaps even ultrasonic bonding takes place, and much lower than temperatures used when hermetically sealing many ceramic packages. Thus there is ample opportunity for such growth to occur.

Kirkendall voids

The compounds are formed by the diffusion of gold and aluminum across their interface. Gold has the greater diffusion rate and, as a result, will leave behind vacancies on the gold side.* This effect is named after Kirkendall because of his studies of the relative diffusion rates in a copper-zinc couple where such an effect was first observed [47S1]. The process of Kirkendall void formation can lead to two kinds of failure: a mechanical stress-induced fracture along the locus of voids and an electrical open-circuit caused by the coalescence of voids.

plagues vs. voids

Because the colorful gold-aluminum compounds were more noticeable than voids, the compounds were believed initially to be responsible for the failures. Thus the use of such terms as the purple, black, or white plagues were coined and many papers were written about which and in what amounts the five different compounds (Au_4Al, Au_5Al_2, Au_2Al, AuAl, and $AuAl_2$ [58H1]) appeared in the bond region and how failure ensued. The importance of the void formation proposed by Cunningham [65C5] was gradually recognized but continuing interest in the compounds themselves prompted Cunningham [67C4] to reiterate later that the exact identification of the compounds, and their colors, relative strengths, etc., are essentially immaterial. The important question is the extent of pore formation which depends on the time-temperature history of the bond.

The kinds of reliability problems that result from gold-aluminum interactions depend on the wire bond type and whether a direct or an expanded contact is used (see figure 2).

electrical failure

Electrical failure can occur when gold wire ball bonds are made to aluminum expanded contacts because of the formation of an annular Kirkendall opening about the bond. This opening is difficult to see because of its small dimensions and because it is often located beneath the outer extension of the ball. The annular opening may be so small that a voltage of a volt or less (such as might be applied in an electrical continuity test) can cause an arc to form across the opening and thereby "heal" the open-circuit (see

*Voids have also been seen on the aluminum side of gold-aluminum interfaces. This has been explained by postulating that the diffusion rates of gold and aluminum are modified when diffusion occurs thru interposed intermetallic compounds [69S3].

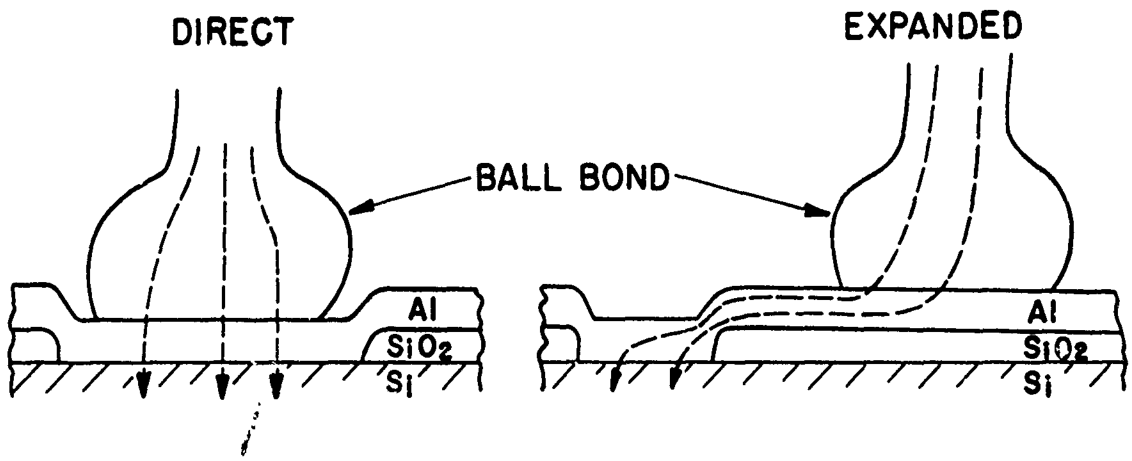

Figure 2. Sketch of a direct and an expanded contact with a gold-wire ball-bond to aluminum metallization. The dashed lines indicate current paths. The sketch is not to scale.

section 5.14.3). The development of these voids at the perimeter of the bond is accompanied by increases in the electrical resistance of the bond with time that can be measured. The rate of increase in resistance with exposure to elevated temperatures is larger for thinner aluminum metallizations [67K2], [67S5], [68A3]. Normally, the bond adherence of these ball bonds is unimpaired by intermetallic compounds which reach to the oxide [65C5], [65H2], [65R1], [66B3], [68A3]. The intermetallic compounds adhere well to silicon dioxide and though brittle can sustain a greater tensile stress than either gold or aluminum [70P2]. Any slight reduction in pull strength after exposure to elevated temperatures is usually attributed to annealing of the wire. If the thickness of the metallization is kept small, void formation is apparently limited because of the small amount of material available for diffusion [66B3].

Mechanical failure can occur when gold ball bonds are made to sufficiently thick aluminum films so that the supply of aluminum for reaction with the gold ball is essentially unlimited. In this case the void formation at the interface results in a mechanically fragile bond after high temperature storage. Howell and Kanz [65H2] found an appreciable reduction in the pull strengths of gold wires bonded to 6 μm thick aluminum films after 44 hours of storage at 200°C. If thin metallization films are used, void formation is apparently again limited. Blech and Sello [66B3] found essentially no change in the average pull strength of gold ball bonds to aluminum films with thicknesses of from 0.05 to 1.0 μm after storage at 200°C for as long as 2000 hours. mechanical failure

Similar degradation can occur if an aluminum wire bond is made to a gold plated terminal where the gold plating is too thick [69K3]. In this

case an increase in the electrical resistance of the bond may be observed. In addition, if the bond deformation is excessive, be it an aluminum wire ultrasonic bond to a gold plated terminal or a gold wire wedge bond to an aluminum film, the brittle intermetallic compounds may extend up into the heel of the bond, and the wire bond becomes very fragile to any bending stress that is imposed, for example, in the initial stage of the pull test or in temperature cycling tests [71P1].

film thickness

Thus, to minimize degradation effects due to gold-aluminum interactions one must avoid bonding to thick metal films and avoid excessive bond deformation. Guidelines by Philofsky [71P1] and Kashiwabara and Hattori [69K3] have been given in section 4.3.

$AuAl_2$ metallization

A patent has been granted for a metal film which inhibits the degradation of gold wire bonds due to Kirkendall voids, by substituting a metal f[illegible] of the intermetallic compound, $AuAl_2$, for aluminum [68T2]. No report of its use has been seen in the literature.

thermocompression bonding

4.5. Thermocompression Wire Bonds

4.5.1. Bonding Process

bonding mechanisms

Thermocompression bonding is a joining process involving the application of pressure at an elevated temperature (not high enough to cause melting) for a certain duration. There is still some disagreement as to how and why the bond occurs [69T2]. No definitive view of the mechanisms involved in the joining process has been found in the literature.

intimate contact

Intimate contact between the two materials to be joined is an essential requirement for making a strong thermocompression bond. This requires that any intervening surface films such as oxides, water, and contaminants be dispersed or penetrated in the process of making the bond. Pressure, temperature, and some lateral spreading of the wire at the interface to disperse any surface films are all presumed to be important factors in achieving this intimate contact. Diffusion is considered by many to be basic to the bonding process [67K1], [69S1], [69T2]. The elevated temperature is thought to promote initimate contact with a minimum applied force by lowering the compressive yield strength of the materials involved and to accelerate diffusion [69S1].

temperature

While it is generally agreed that the bonding temperature should be lower than the lowest eutectic temperature of the metal system, Baker and Bryan [65B1] also mentioned the importance of the bonding temperature being below that at which dislocations may form or be displaced in silicon. In this regard it is interesting to note that Goetzberger [61G1] has reported the generation of dislocations in the emitter-base junction as a result of

bonding at 320°C. However, the possibility that excessive pressure could also have generated these dislocations cannot be ruled out.

yield point

Another requirement for a strong thermocompression bond is that the wire have a sufficiently low yield point at the bonding temperature so that when the joining pressure is removed the relief of the stresses will not tend to restore the wire to its original shape and thereby weaken or rupture the bond [66M2], [69S1].*

4.5.2. Bond Types

Characteristics of ball, stitch, and wedge thermocompression bonds are summarized in table 1. The most common thermocompression wire bond consists of a ball bond to the die and a stitch bond to the terminal. The bonding sequence for this wire bond is sketched in figure 3.

ball bonds

Only gold wire is used to make thermocompression ball bonds. Aluminum wire is not used because the oxide formation during flame-off prevents the formation of an aluminum ball. Baker and Bryan [65B1] attempted to form aluminum balls by a variety of heating methods, even in protective atmospheres, but were unsuccessful in obtaining balls of uniform size. More recently, Kessler [70B2] has reported preliminary success in forming aluminum balls by passing a jet of inert gas heated to about 1000°C across the wire. His purpose was, however, to make aluminum balls for ultrasonic bonding.

stitch bonds

When stitch bonds are made at both ends of the wire, a mechanism is required for cutting the wire and for making a right angle bend in the wire. The bend is required so that when the wire is retracted up the capillary the bent portion of the wire may be positioned against the capillary in preparation for the next bond. Scissor cut-off techniques which also bend the wire-end as desired are described by Köllner [66K3] and by Rasimenoks *et al.* [67R4]. Here too, as in figure 3, the remaining upright wire from the second stitch bond of the sequence must be removed as part of a separate operation unless this step is incorporated in the machine operation. Helda and La Point [68H5] describe a means for removing the upright wire after the last stitch bond is made. The bonding tool is raised slightly and vibrated to metal-fatigue the wire adjacent to the bond. While the tool is vibrated it is also moved horizontally away from the bond to break the wire there and also to bend the wire extending from the bottom of the tool in a way which will facilitate the making of the next stitch bond.

second stitch bond

After making a stitch bond to the last bonding area a second stitch bond is sometimes made before the wire is cut. This is done as a precautionary

*Actually, Madland *et al.* [66M2] expressed this requirement in terms of modulus of elasticity and Slemrons [69S1] in terms of ductility of the bonded materials.

Table 1 - Characteristics the Ball, Stitch, and Wedge Thermocompression Bonds

Bond Type	Characteristics
Ball	1. The bond is made with a capillary tool after the end of the gold wire has been formed into a ball as shown in figure 3. 2. Reputation for being the most uniformly rugged. 3. Orientation freedom — the second bonding site does not need to be aligned with respect to the bonding machine. 4. Relatively large bonding area is needed to accommodate the ball (~ 2.5 times the wire diameter). 5. Strength of wire bond is limited by the tensile strength of the wire just above the ball which has been fully annealed during flame-off.
Stitch	1. The bond is made with a capillary tool. Figure 3 shows the making of a stitch bond after a ball bond has been made. 2. Bonding area needed is less than for the ball bond. 3. Stitch bonding sites must be aligned with the direction of the wire feed and the bonding machine to avoid twisting the wire adjacent to the bonds. 4. Wire is deformed at the bond so that a significant reduction occurs in the wire cross-section adjacent to the bond.
Wedge	1. The bond is made with a wedge-shaped tool as indicated in figure 4; the wire must be aligned separately. 2. Bonding area needed is smaller than that needed for stitch and ball bonds. (Hence they are often used in high-frequency devices and where the bonding areas are closely spaced.) 3. Slower procedure because wire must be aligned separately under the tool. 4. Bonding sites must be aligned with the direction of the wire feed and the bonding machine to avoid twisting the wire adjacent to the bonds. 5. Wire can be deformed at the bond so that a significant reduction occurs in the wire cross-section adjacent to the bonds.

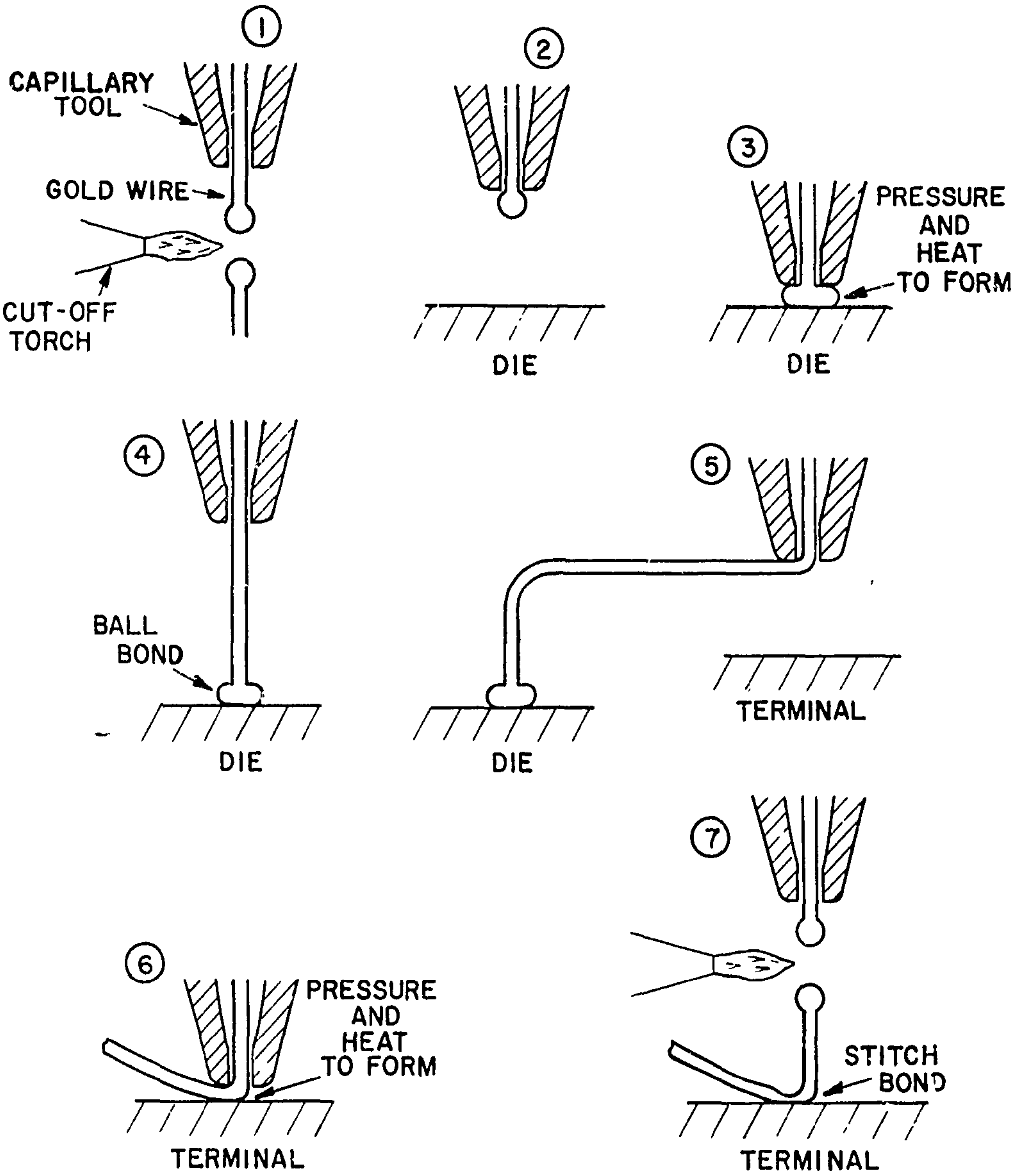

Figure 3. Procedure for making a ball-stitch wire bond: (1) Gold wire is fed thru the capillary type bonding tool; a small flame is passed across the wire below the bottom of the capillary to melt the wire and, by surface tension, form a gold ball at the end of the wire. (2) The wire is retracted so that the ball is held against the bottom of the capillary tool. (3) The tool is lowered to the contacting surface where the gold ball is pressed against the contacting surface and the interface is brought to the bonding temperature to form a bond. (4) The tool is raised with the wire bonded to the surface. (5) The bonding surface on the terminal is positioned beneath the bonding tool. (6) The tool is lowered as in step 3 to make a bond. This bond and any subsequent bonds made before the wire is cut again are called stitch bonds. (7) After the last stitch bond is made, the capillary tool is raised as the wire is paid out and a flame is moved across the wire to sever it and form a ball on each end of the wire.—The bonder is then ready for the next bonding cycle and to make another ball bond. The upright wire extending from the stitch bond is removed by manually pulling the wire. The wire will rupture adjacent to the stitch bond because of the reduced wire cross-section there. Grable and Patzer [69G2] have described a technique for avoiding this separate procedure. After making the last stitch bond the capillary is raised slightly and a wire clamp is activated and pulled backward to rupture the wire. The capillary is then raised and a flame swept across the wire end to form a ball in preparation for the next bonding cycle.

measure to reduce possible degradation of the bond by the process of pulling the wire [71B2]. However, no clear evidence of such degradation has been reported.

wedge bonds

Wedge bonds are made with a wedge tool instead of the capillary tool used for stitch bonds. Most wedge tools for thermocompression bonding do not have a wire-guide hole, so an additional mechanism is required to align the wire beneath the tool. Otherwise, the bonding procedures are similar to those for stitch bonding. Stitch and wedge bonds are usually made with gold wire but aluminum wire may also be used. In the latter case, a hot inert gas has been used both to heat the wire and bonding pad and to reduce the oxidation of the aluminum wire. Johnson [68J1] has described the use of such a hot-gas technique for thermocompression bonding. Hill and Wrench [68H3] found that use of a pulse-heated capillary tool facilitates bonding with aluminum wire.

eyelet bond

As a result of their interesting studies of the plastic flow of metal which occurs during the wire deformation in the bonding process, Baker and Jones [66B4] have suggested an improved wedge bond which they called the eyelet-bond. By using a specially designed tool, the lateral plastic flow of the wire at the wire-metallization interface is increased without significantly reducing the wire cross-section in the process of making the bond. Sketches of the tool and an eyelet bond are shown in figure 4 with a typical wedge tool and bond. They reported eyelet bonds to be superior in strength and in reproducibility to ordinary wedge and ball bonds of the same metal combinations. The problem of the separate alignment of the wire under the

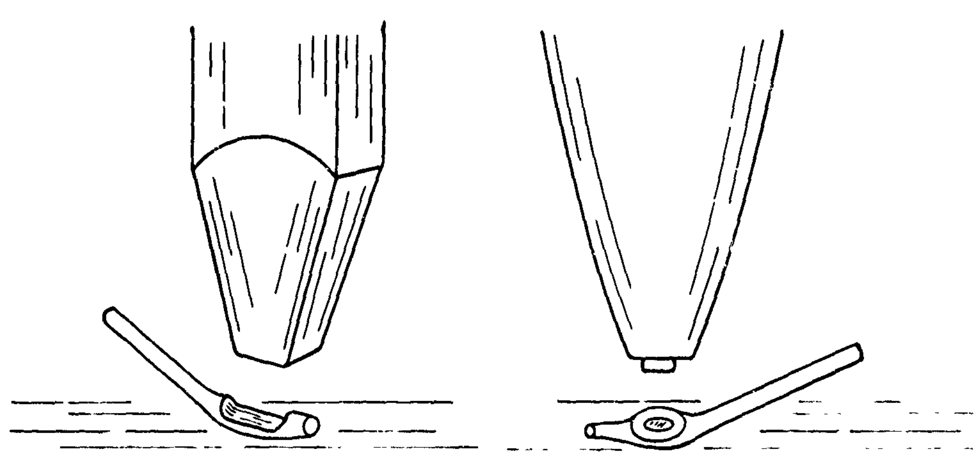

Figure 4. Sketch of typical wedge (left) and eyelet (right) bonding tools and the wedge and eyelet bonds made with these tools. Capillaries to feed and align the wire are not shown.

tool required for wedge bonding is aggravated in the eyelet bond because the wire now must be aligned directly under the central projection on the face of the bonding tool (see figure 4). The optimum diameter of this projection was reported to be equal to the diameter of the wire used. This severe alignment problem may be a reason for the lack of more recent reports of the use of eyelet bonding.

4.5.3. Conditions and Factors in Fabrication

The three primary conditions in thermocompression bonding are force, temperature, and time. In optimizing these conditions to make a reliable wire bond it is important to realize that not only are they interdependent but they are affected by other conditions and factors. Minor changes in these variables can cause significant differences in the bonding characteristics. Consequently, it is necessary to optimize experimentally the force, temperature, and time. More than one combination of values for these three conditions may produce a satisfactory bond. Of these combinations, Slemmons [69S1] suggested that the most desirable bonding occurs with a combination where the values for the force, temperature, and time are the lowest. It may be assumed that this guideline includes such considerations as the following: Short bonding time is desirable for production purposes. Low bonding temperature is desirable to avoid degradation of the wire bonds due to gold-aluminum interactions of the device due to alloying, and of the passive components due to temperature-induced material decomposition in hybrid devices. Low pressure is desirable to avoid fracturing or otherwise damaging the silicon beneath the bond. An additional guideline can be recommended in the interest of reproducibility. The bonding schedule should also be selected so that the sensitivity of the quality of the wire bond to variations of these three conditions is minimized which may not necessarily correspond to the above mentioned combination.

bonding schedule

guidelines

In general, the thermocompression bonding process is regarded as simpler and more forgiving that the ultrasonic bonding process, to be discussed later. Some of the factors and parameters that have been mentioned in the literature pertain to achieving a high joint strength between the metal bonding surface and the wire. For most cases, however, it is not the bond itself but rather the wire that is the weakest link in the wire bond. In ball bonds the weakest link occurs in the high-temperature annealed wire leading into the bond; in stitch and wedge bonds it occurs in the region of the wire in which the cross-section has been reduced by the bonding tool.

bond and wire strength

A number of comprehensive review papers have been published which deal with the various conditions and factors considered to be important in the making of reliable thermocompression wire bonds [64H2], [65H2], [67K1].

reviews

Some of the highlights of these and other papers are included in the paragraphs that follow.

force

The bonding forces generally recommended are of the order of tens of grams-force. Too large a force may damage the semiconductor substrate or excessively deform the wire. Often the force suggested is defined in terms of the degree of deformation produced, of the order of 50 percent of the wire thickness [64H2], [68K1]. Factors such as wire hardness and size, bonding temperature, and tool design are therefore important. Budd [69B3] found that the bonding strength of gold wire thermocompression bonds to a variety of thick-film conductors was significantly less sensitive to variations in applied force than bonds made to thin-film metallizations.

temperature

The typical range of bonding temperatures specified is from about 300 to about 350°C. The five different ways that have been used to bring the interface temperature to the desired level during the bonding procedure are listed with comments in table 2. Howell and Slemmons [64H2] stressed the importance of controlling the interface temperature, once selected. They considered a variation greater than ±5°C to be excessive for achieving uniform bonding characteristics. Such control may be difficult to achieve in practice, however, and no data are available to indicate the sensitivity of the quality of the wire bond to such variations in interface temperature. Antle [64A1], [66A1] proposed an interesting method for selecting an optimum interface temperature after which optimum force and bonding time could be experimentally determined. He noted that, theoretically, bond strength should be directly proportional to the coefficient of friction between the materials to be bonded, measured at the bonding temperature. Thus, by measuring the variation of the coefficient of friction with temperature for various metal systems and conditions, the optimum interface temperature and how carefully it should be maintained may be determined. To support his proposal, Antle showed a correspondence of a peak in the coefficient of friction and in the shear bond strength with temperatures for silver wire on gold film. Further exploration of this relationship has not been reported in the literature.

time

The range of bonding times generally used extends from a large fraction of a second to several seconds depending on the magnitude of the bonding temperature and applied force. The control of the time is more important when the pulse heated capillary [68H3] is used than when the other heating methods are used. Because the maximum interface temperature is obtained at the end of the heating pulse, the bonding time in this technique effectively controls the peak interface temperature for bonding.

ball size

One of the factors that must be considered when making ball bonds is the variation in the size of the ball formed in the flame-off procedure. Such variation in ball size should be minimized because, for the same applied

Table 2 - Methods for Attaining Thermocompression Bonding Temperature

Methods	Comments
I. Heat Device-Holding Stage	a. Inconvenient delay to bring device to desired bonding temperature, especially for device packages with low thermal conductivity. [67K1]
	b. Long time at bonding temperature required for complex devices with many wire bonds leads to excessive formation of Kirkendall voids and intermetallic compounds when gold-aluminum interfaces are involved. Degradation of other components may also occur. [68H3]
	c. Variations in bonding interface temperature from bond to bond may occur, for example, due to: 1. excessive air currents 2. progressive heating of tool 3. voids in die-to-header solder or other factors affecting heat transfer. [64H1], [67K1]
II. Heat Tool	a. Allows more rapid bonding and less heating to device than method I. [67K1]
	b. Tool must be heated to a temperature higher than the bonding temperature because the device and stage will act as a heat sink.
	c. At these higher temperatures ($\gtrsim$ 350°C) both the capillary heaters and the tungsten carbide tools tend to wear out faster. [67K1] Also, gold wire at this temperature will tend to deform excessively while bonding. [68H3]
III. Heat Stage and Tool	a. The temperature of both the stage and tool can be lower than in either of methods I or II with consequent reductions in the problems cited.
IV. Pulse Heat Tool (one pulse per bond)	a. Device exposed to bonding temperature for only a short time (no thermal shock related problems encountered with capillary tool or substrates used). [68H3]
	b. Tool wear is much less than if method II is used. [68H3]
	c. Pulsed heating must be adjusted for different substrates (in most hybrid circuits the heating is adjusted to make bonds to the substrate requiring the most heating). [68H3]
V. Heat Bonding Interface by Hot-Gas Jet	a. Inert gas is used to bring bonding interface to bonding temperature. The tool, substrate, or both may also be heated. [68J1]
	b. Method reported useful for bonding aluminum wire. Hot inert gas serves dual function of heating and preventing oxidation. [65R1]

force, a ball larger or smaller than normal is subjected to insufficient or excessive deformation, respectively. A small ball may also become wedged in the capillary and halt further bonding until the capillary is either cleared or replaced. The size of the ball is affected by the speed at which the flame-off torch passes the wire, the size and consistency of the flame, and general ambient conditions in the work area [65H2], [67K1], [68H3]. Hill and Wrench [68H3] recommended the use of a torch with a ruby orifice to improve the consistency of the flame cone.

flame-off torch

tool material

Most capillary bonding tools are made either of tungsten carbide (with a cobalt binder) or of glass. Recently, tools of other materials such as titanium carbide, sapphire, and ceramics have become available with claims of superior wearing properties to those of tungsten carbide. Other things being equal, the bonding schedule is affected by using tools of different materials at least to the extent that the thermal conductivities are different.

tool finish

tool wear

A smooth tool surface is considered important to prevent the wire from sticking to the tool after bonding; a 0.5 μin. (0.025 μm) finish has been suggested [64H2]. The bonding surface of the tool wears with use. Alloying of the gold in the wire with the cobalt binder in the tungsten carbide tools leads to roughening and chipping of the bonding face of the tool. Titanium carbide tools do not require a binder and hence may wear less quickly. Operating life of a bonding tool depends on the operating temperature history as well as general care and skill of the bonding operator. Capillary tools for making ball bonds may also wear along the inner diameter of the capillary at the bonding end of the tool. In this case, the gold from the ball is extruded up into the capillary tending to reduce the diameter of the wire leading into the ball. Under these conditions bonding pressure on the ball is small and non-uniform.

tool area and edges

The tool contact area and the radii of curvature of the tool contact surface edges should be such that bonds with adequate contact area may be achieved without excessive deformation or abrupt changes in the wire cross-section. A radius of curvature from one to four times the wire radius is usually recommended.

wire alignment

wire spool

The importance of wire alignment in the making of consistent wedge bonds so that the wedge makes contact with the wire in the same way each time was pointed out by Howell and Slemmons [64H2]. They suggest that the location of the wire-feed assembly be as close as possible to the tool so that maximum support and control can be exerted. In addition, the wire spool should be large to minimize curvature of the wire and it should have only a single layer of wire to avoid distortion and cohesive bonding between successive layers.

Considerations for selecting a satisfactory range of loop heights are as follows: Too small a loop height results in excessive bending of the wire immediately above the ball bond. The wire may also be subjected to significant tensile and bending stress as a result of differential thermal expansion of the wire and connected components (see section 5.13.3 for further remarks on this topic). Too large a loop height makes the system less rigid and subject to short-circuits with other elements of the device and package as a result of accelerational stress.

loop heights

4.6. Ultrasonic Wire Bonds

ultrasonic bonding

4.6.1. Bonding Process

In the ultrasonic bonding process ultrasonic energy and pressure are used to achieve intimate contact of the wire and metal in a way which results in a bond at their interface. Both the pressure and ultrasonic energy are transmitted by a bonding tool which presses the wire against the bonding surface and is vibrated at a forced ultrasonic frequency, typically about 60 kHz. The applied force establishes and maintains adequate physical contact prior to and during the time that the bonding tool is energized. Prior to the application of ultrasonic energy, the applied force deforms the wire somewhat. The actual area of contact is much smaller than the apparent area of contact because of the sub-microscopic surface roughness which exists. With the application of ultrasonic energy the temperature at the interface rises, the wire is deformed further, and the interfacing surfaces are smoothed, increasing the area of contact. Surface oxides and any other surface films are disrupted and dispersed, and nascent metal surfaces are thus brought into contact in a way which results in a bond.

intimate contact

wire plasticity

The plasticity of the metal during the process results not only from the temperature rise at the interface region but also from the ultrasonic energy as well [68B1]. For aluminum the application of sufficient ultrasonic power density has the effect of reducing the stress necessary for plastic deformation during exposure and hardening aluminum after exposure; increasing the temperature while the ultrasonic energy is applied decreases the hardening effect [66L3].

US softening and hardening

mechanisms

The mechanisms involved in the actual bonding process are not fully understood [65J1], [68B1], [69P1], [71J2]. The results of early and extensive studies of ultrasonic bonding by Weare *et al.* [60W1] suggested an interface melt hypothesis in which bonding was due to the formation of a thin molten film at the interface, caused by the dissipation of ultrasonic energy there. Bikerman [66B6] asserted that this was the only way an adhesive bond could be made. More recently, Uthe [69U1] has been a proponent of the existence of an interface melt, however thin it may be. Thus, the ultrasonic

melt hypothesis

bond could be called a "hot pressure bond" because of the pressure and high interface temperatures involved.

disagreement

Others have disagreed with the interface melt hypothesis and instead have proposed that the process is much more complex [62P1], [65J1], [67J1], [71J2]. Peterson *et al.* [62P1] and later Jones [67J1] made temperature measurements which led them to conclude that the maximum interface temperature achieved was between 30 and 50 percent of the melting temperature of the metal having the smaller melting temperature. Joshi [71J2] measured bond interface temperatures while bonding wires of gold, aluminum, and copper to gold-plated copper-constantan thermocouple beads ground to the shape of a small thin disc and rigidly held by embedding in epoxy. He reported temperature increases of less than 70°C during bonding. When a deliberate decrease in the bonding force was made, to promote slippage at the bonding interface and thereby increase frictional heating, a temperature increase of 120°C was measured when bonding gold wire. Jones *et al.* [65J1] stated directly that no evidence for a melted zone has been seen and further that heat by itself does not appear to play a significant role in the bonding process. Joshi [71J2] has concurred. Supportive evidence to indicate that achieving a high temperature during bonding is not important has been provided recently by Joshi [71J2] and Harman and Leedy [72H1] who have made gold-to-gold and aluminum-to-aluminum ultrasonic wire bonds, respectively, at liquid nitrogen temperatures. Metallographic examinations of bond cross-sections of a variety of similar and dissimilar metals have been reported [62P1], [65J1], [71J2]. These examinations have revealed a number of interfacial effects, such as interpenetration, and surface film disruption and dispersion; working effects, such as plastic flow, grain distortion, and edge extrusion; and heat effects, such as recrystallization, precipitation, phase transformation and diffusion; but no unifying concept of the ultrasonic bonding process has been formulated.

temperature measurements

metallographic exam

weld formation

The initiation and growth of the welded area appears to occur at distinct localized regions as described by Jones [67J1] rather than in a generally continuous way from the center of the contact area outward to the edge of the wire contact, as postulated by Uthe [68U2-4]. Scanning electron microscope observations of welded areas as the bonding power and time is increased have been reported by Leedy [69B3], [70B8]. Bonding was initiated at discrete spots generally at the heel or toe of the contact area (under the back or front of the bonding tool). Initiation points appeared randomly in these areas from bond to bond. With greater power and time these discrete bonding sites expanded, and grew along the sides. Bonding at the center generally did not occur. A development of such bonding sites is shown in the sequence pictured in figure 5. In figure 6, a SEM photomicrograph of a lift-off pattern and one of a partially lifted bond illustrate the lack of bonding to the central region. Silicon precipitates in the aluminum wire were postulated as

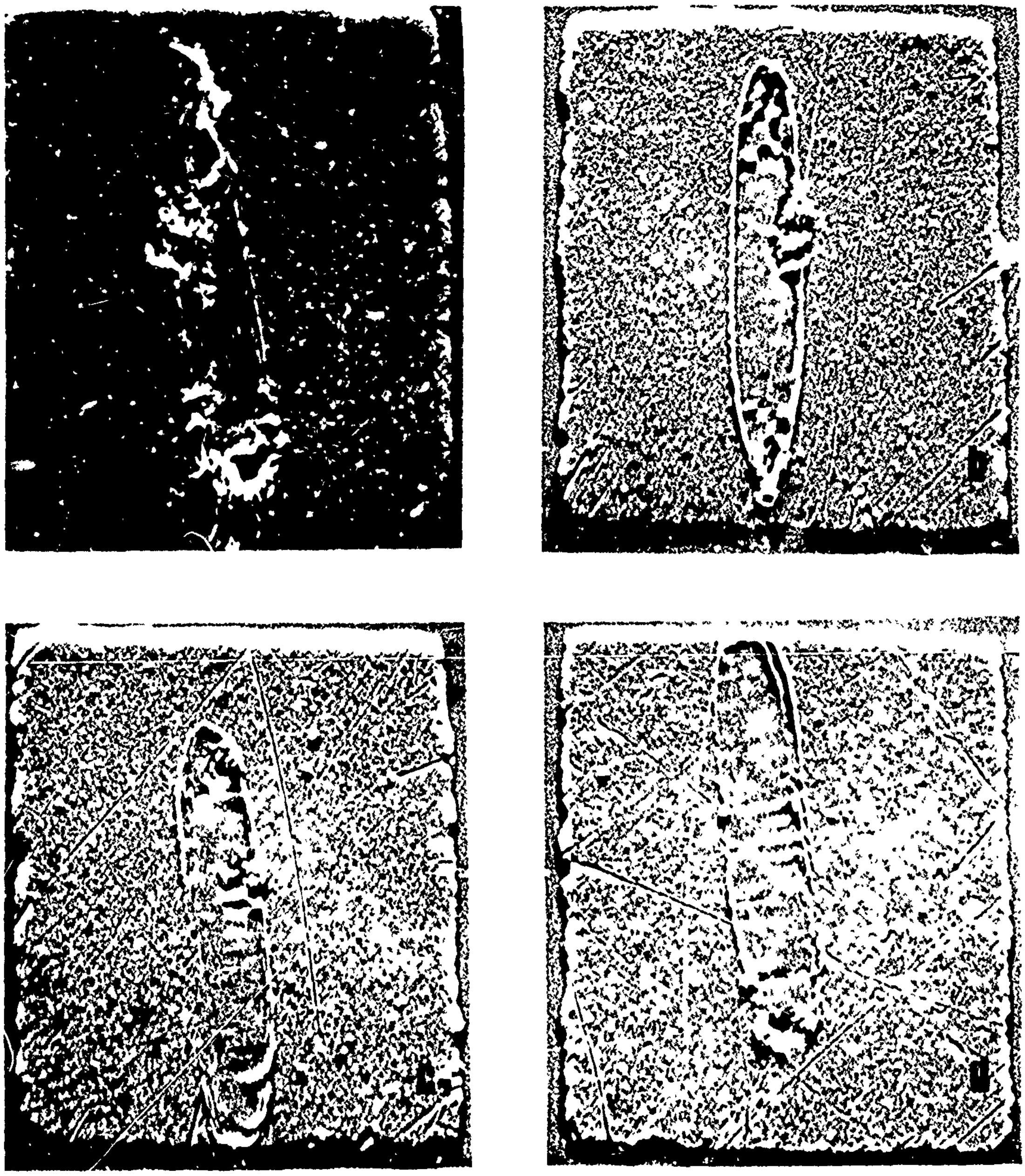

Figure 5. SEM photomicrographs (460 X) of bond adhesion (lift-off) patterns for first bonds made at different time settings and constant force and ultrasonic power settings. The time is longest for case *a* and is decreased to the shortest value for case *d*. Settings used in case *a* result in a bond which will adhere to the pad; the shorter time settings do not produce an adherent bond. The surface of the bonding pad under the wire is smoothened by the lateral movement of the wire produced when the tool is brought down on the wire with the selected force and before ultrasonic power is applied. Note the apparent movement during bonding exhibited in case *d*. This is thought to result from mechanical vibration in the bonding machine. (From Leedy [70B3])

Figure 6A. SEM photomicrograph of the lift-off pattern of a normal bond made under laboratory conditions. The pattern, which clearly reveals the unwelded center portion of the bonded region, was exposed by carefully peeling back the bond. Magnification: 510 X. (From Leedy [70B8])

Figure 6B. SEM photomicrograph of the lift-off pattern of a partially removed bond made under laboratory conditions. A similar pattern can be observed on both the wire and the pad. Again the center portion of the bonded region is not welded. Magnification: 900 X. (From Leedy [70B8])

the nucleating centers for the initiation points, but preliminary observations with magnesium-doped aluminum wire, in which magnesium does not precipitate, showed similar bond growth patterns. Recent investigations by Kessler [72B2] of lift-off patterns of ultrasonically bonded aluminum ribbon wire, have indicated that the way welding proceeds spatially may be dependent on the bonding schedule: for a high-power, short-time bonding schedule, primary welding occurred at the perimeter of the wire; while for a low-power, long-time bonding schedule, primary welding occurred in the central region as well as at the perimeter of the wire.

intimate contact

Aluminum wire is commonly used in making ultrasonic wire bonds. Uthe [69U1] cited two factors responsible for the relative ease with which aluminum wire ultrasonic bonds could be made: (1) the abrasive action of the aluminum oxide (from the oxide coating) in an oxide-aluminum slurry cleans and extends the bonding area and (2) the tensile strength of aluminum decreases with temperature so that the soft, conforming aluminum adjacent to the interface can be well supported by the outer and cooler parts of the wire. Contradicting the suggested importance of these two factors are the generally non-continuous way that bonding proceeds, which does not easily

fit with the concept of an oxide-aluminum slurry, and the relative unimportance of temperature in bonding. The softening needed to achieve intimate contact appears to be produced by absorption of ultrasonic energy [71J2], [72H1]. Furthermore, gold which does not have an appreciable oxide nor the strength-temperature characteristics of aluminum can also be bonded ultrasonically [65J1], [68S1], [71G2], [71J2]. While no detailed studies have been reported which have examined the relative ease of making aluminum and gold wire ultrasonic bonds, Joshi [71J2] has at least indicated no significant differences in their bondability.

Ultrasonic bonding is a more critical process than thermocompression bonding. The principal reasons are that the ultrasonic energy transmitted to the wire and the bonding surfaces must be inferred and there is no clear understanding of how this energy and its rate of transmission is related to making a satisfactory wire bond. Furthermore, a number of conditions and factors (discussed in section 4.6.3) mutually affect the energy transmitted to make the bond in ways that are usually not clear. Nevertheless, with sufficient control of the empirically desired fabrication procedures highly reliable wire bonds can be made. Two important advantages that ultrasonic bonding has over thermocompression bonding are that it is fast and that no heating is required [67K1], [68H3], [69S1]. US vs. TC bonding

The process as normally used with a wedge tool which is lowered and raised by pivoting, has three limitations that become particularly acute in hybrid circuits [68H3]: (1) the bond surfaces must be uniformly rigid, (2) the height of the die and terminal bonding surfaces cannot vary greatly from device to device, and (3) the device must be rotated to align the two bonding sites with the wire.* The first requirement relates to the need to couple the ultrasonic energy into the bonding area. The other two requirements are relaxed if ultrasonic ball-stitch bonding with gold wire is used because the tool moves vertically to and from the bonding surface and there is no need to align the two bonding sites to avoid twisting the wire in moving from the first to the second bonding site. Consequently, gold-wire ultrasonic bonding is finding more use in hybrid circuits [70E1]. limitations Au-wire US bonding

4.6.2. Fabrication Procedure

A simplified procedure for making an ultrasonic wire bond between the terminal and the semiconductor die of a device with a typical wedge tool is sketched in figure 7. Usually there is insufficient room for the tool if the first bond is attempted on the die. Hence the first bond is usually made to the terminal as shown. The procedure for making ultrasonic bonds figure 7

*Such rotation is inconvenient and it can contribute to operator error in devices with complex bonding pad location patterns [71B2].

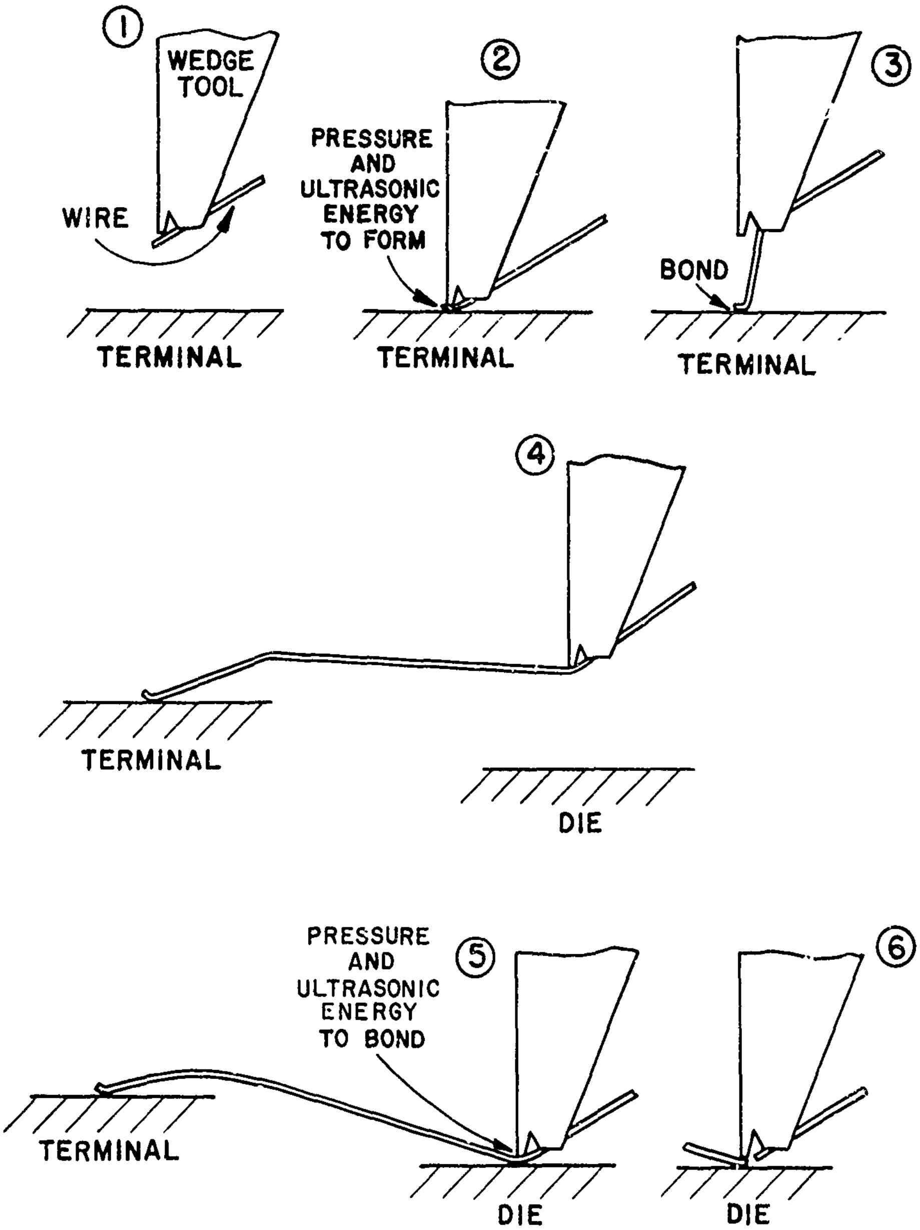

Figure 7. Simplified procedure for making an ultrasonic wire bond between a package terminal and semiconductor die with a typical wedge-type tool. (1) Wire is located between the bonding surface of the tool and the terminal bonding area. The bonding tool is then lowered to its "first search" position (75 to 125 μm above the bonding surface). This position is preselected and determined by the average height of the surfaces to which the first bond is to be made. (2) The tool is lowered to press the wire against the bonding surface with a predetermined force. Ultrasonic energy is applied for a preset time to make the first bond. (3) The tool is raised while the wire is paid out from the spool of wire (not shown). (4) The bonding stage holding the device moves the second bonding site under the tool and the tool is lowered to its "second search" position (similar to steps described in 1). (5) The tool is lowered to make the second bond as in 2. (6) After the second bond has been made, a wire clamp to the rear of the tool (not shown) closes and pulls back on the wire to break the wire at the heel of the bond. The tool is then raised and the end of the wire is fed out underneath the tool until the end is located somewhat beyond the front of the tool, as shown in 1. The bonder is ready to be located over the next first bond site to repeat the bonding cycle.

with a capillary tool is similar except that means for bending the wire under the tool for the first bond are needed. If gold-ball ultrasonic bonds are to be made, the additional step of forming the ball is required. This has been described in the thermocompression bonding section.

Prior to the procedure in making a wire bond with a wedge tool, such as sketched in figure 7, an alignment procedure must be performed. The stage holding the device must be manipulated by the operator to align the two bonding sites so that they lie under and in line with the direction of the wire. This is done to avoid twisting the wire at the heel of the first bond while moving the second bonding site beneath the bonding tool.

alignment

4.6.3. Conditions and Factors in Fabrication

The three primary conditions in ultrasonic bonding are the force, time, and ultrasonic power. The ultrasonic power available to make the bond is dependent on not only the power setting of the oscillator power supply but also the frequency adjustment and other more subtle variables to be discussed later. The force used in bonding must be large enough both to hold the wire in place without slipping and to couple the ultrasonic energy into the bonding locale without producing excessive deformation of the wire [67J1]. It is generally of the order of tens of grams-force. The specific value selected depends on a number of factors, some of which are the size and design of the bonding tool face, the size and hardness of the wire, and the sensitivity of the substrate and any adjacent active areas to the bonding pressure. Order of magnitude values for the input power to the transducer and the bonding time are a few watts and tens to hundreds of milliseconds. A preference has been expressed for a high-power, short-time to a low-power, long-time combination to avoid metal fatigue and the initiation of internal cracks [65J1], [68U4]. On the other hand a lower power and longer time schedule than usually used has produced bonds with a better cosmetic appearance and a greater pull strength when ribbon wire was used [72B2].

US power

force

time

schedule

No definitive values for the parameters of force, time, and power can be given for an optimum bonding schedule. Only general recommendations can be given which may be used in adjusting a given bonding machine for particular wire, bonding surfaces, semiconductor die, and package characteristics. This is because many subtle factors can affect the quality of the wire bond. Also, the uniqueness of each bonding machine must be considered in developing the optimum bonding schedule because of the slight differences in friction, looseness, rigidity and other mechanical tolerances [69U1].

bonding schedule

The general guiding philosophy for establishing the optimum bonding schedule is that the bonding parameters be adjusted so that it is the reproducibility of the process rather than the strength of the wire bond that is maximized. That the strength of the wire bond may need to be compromised to

schedule guidelines

achieve greater control over the process [67R1], [69K1], [70B8], can be seen from the following remarks. The primary criterion for strength in optimizing the bonding schedule is the pull strength of the wire bond as measured in a pull test (see section 5.3). There are two primary failure modes in the pull test: rupture of the wire adjacent to the bond, where it has been deformed and reduced in cross-sectional area, and rupture or lift-off of the bond at the interface between the wire and the metal film. A useful schematic representation is shown in figure 8 where the rupture strength of the bond and the tensile strength of the deformed wire adjacent to the bond are plotted as a function of ultrasonic power, after Kashiwabara *et al.* [69K1]. The sketch shows with the dashed and dotted lines that as the power increases, the tensile strength of the deformed wire decreases, indicating an increase in wire deformation, while at the same time the adhesion strength of the bond itself increases rapidly above some level of ultrasonic power. The failure mode and the pull strength is determined by which of the two broken curves is lower. The shaded stripe indicates the expected dependence of the pull strength on the power setting for a single-bond pull test. The cross-over point, at P_c, is altered by the time and force settings of the machine as well as other factors (to be discussed later). For example, when the force and time are reduced, P_c is increased without any reduction in the maximum pull strength [69K1]. Uncontrolled small variations in the bonding conditions will cause larger variations in the pull strength in the region where bond failures are expected because of the steepness of the slope of the bond strength curve, as shown in figure 8. The width of the shaded stripe is meant to indicate the variation in pull strength for a given power setting. Thus, if in this case the ultrasonic power is selected to achieve a maximum pull strength, a larger variation in pull strengths will be expected. This indeed has been found to be the case and has been the basis for the suggestion that the bonding schedule not be adjusted for maximum pull strength [69K1], [70B8] because of the penalty of a greater variation in pull strength.

figure 8

optimizing schedule

pull strength

The dependence of pull strength on ultrasonic power indicated by the shaded stripe in figure 8 is similar to the dependence reported by Leedy [70B8] of pull strength* with not only power, but with bonding time or with bonding force. Similar curves of such dependencies have appeared elsewhere [69P1], [70D2], [70P1], but for double-bond pull tests in which failure was allowed at either end of the wire bond. In these curves the pull-strength maximum is sometimes more centrally located. The use of such curves to achieve an optimum bonding schedule has been described by Plough *et al.* [69P1], Davis [70D2], and Leedy [71B5].

*Bonding machine settings were adjusted so that failures occurred only at the first bond of the single-level wire bonds tested.

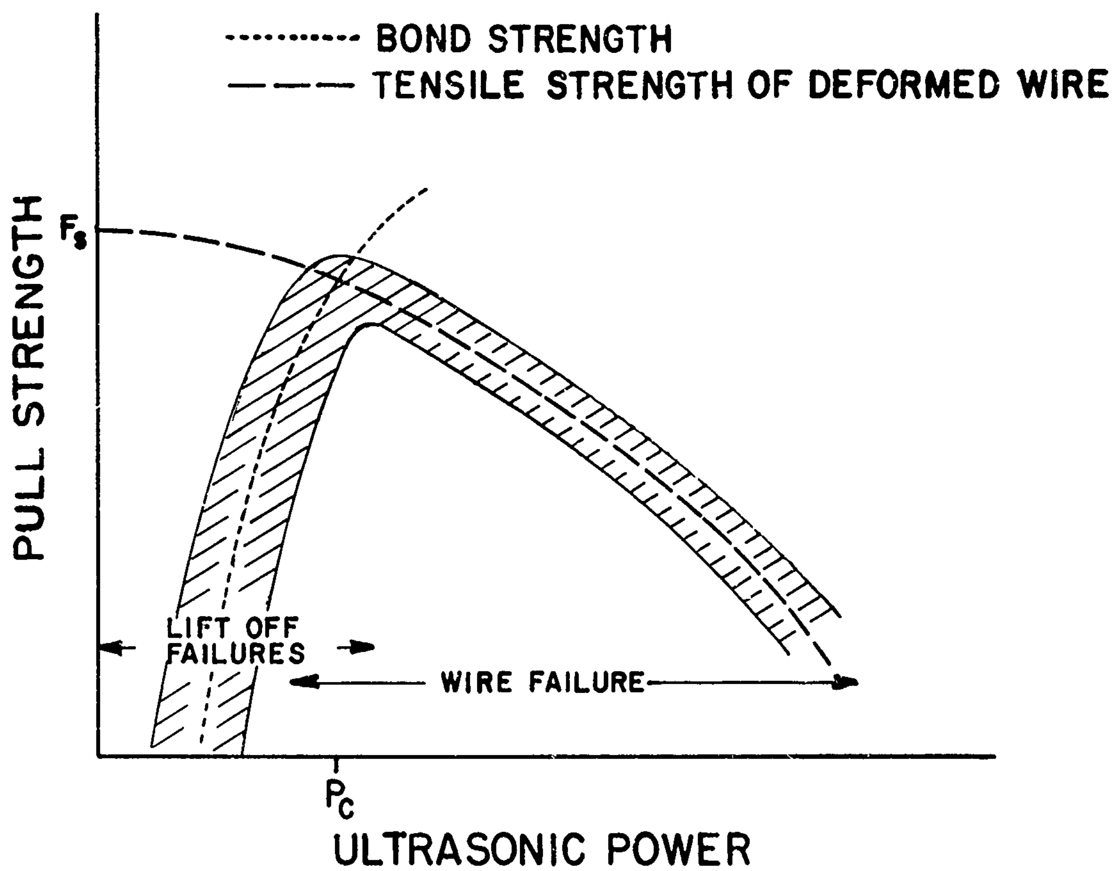

Figure 8. Schematic dependence of the pull strength of a single bond on the ultrasonic power setting of the bonding machine. This is drawn from the schematic dependencies on the ultrasonic power of the adhesion of the bond and the tensile strength of the heel of the bond. The width of the shaded curve is meant to indicate the expected variation in pull strength because of uncontrolled variations in the bonding process, and other variables. The critical power setting, P_c, determined by the crossover of the dotted and dashed curves indicates a broad dividing line below which lift-off failure and above which wire failure is expected in a pull test. F_s represents the tensile strength of the undeformed wire.

The quality of the wire bond is also judged by wire deformation at and near the bond as well as by other features. This is discussed in sections 5.2 and 5.16.

4.6.4. Factors Related to Bonding Equipment

4.6.4.1. Introduction

Many of the factors that can affect bonding are associated with the bonding machine. The basic components of the ultrasonic bonding machine and its accessories are sketched in figure 9. Basic requirements for making consistently high-quality wire bonds are: the precision control of the mechanical movements, the rigidity of the mechanical components and the bonding

requirements for process control

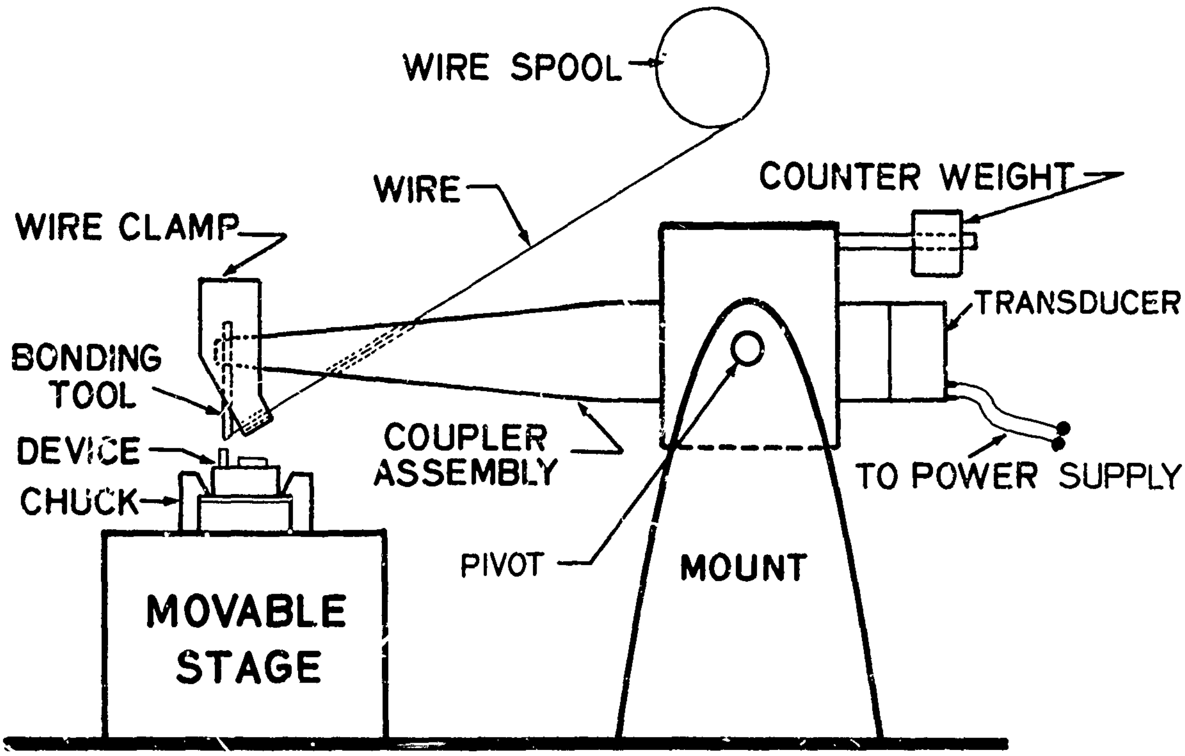

Figure 9. Sketch of an ultrasonic bonding machine with basic components and accessories labeled.

surface, and the absence of mechanical vibrations [69U1], [70D2], [71H1], [71J1]. The application of capacitor microphones and magnetic pickups for diagnosing both mechanical and electrical problems in wire bonding equipment have been described recently by Harman and Kessler [71H1]. They were able, for example, to detect excessive relative movements between the tool and bonding surface which could be traced to the cantilever type supports for the transducer-coupler assembly housing, operation of the cam motor, and vibration or shock transmitted through the floor or base. Uthe [69U1] has also suggested tests for diagnosing bonding problems, many of which are related to the bonding equipment.

4.6.4.2. Ultrasonic Power Supply

resonance

The ultrasonic power supply generally has two channels to provide different power levels and bonding times for bonding to the semiconductor die and terminal bonding surfaces, respectively. The ultrasonic frequency is adjustable about a mean frequency of approximately 60 kHz to allow tuning the system to resonance, where the transmission of ultrasonic energy to the bonding

area via the bonding tool is most efficient. The system is designed to deliver significant energy only within a limited frequency range about this mean frequency. The extent of this frequency range is determined by the Q of the electro-mechanical system.

tuning to resonance

A preliminary step in adjusting the bonding machine is to tune the power supply to achieve a resonance of the mechanical system driving the bonding tool. In some power supplies the procedure recommended by the manufacturer is to tune to electronic resonance. However, the interaction of the electrical and mechanical systems is complex, and Harman [69B6] has shown that the conditions for electrical and mechanical resonances may not necessarily coincide. To avoid this and other problems Harman and Kessler [71H1] have described procedures for tuning the bonding machine and reproducing a specific ultrasonic vibrational amplitude at the end of the bonding tool. Control and reproducibility of the tool tip vibrational amplitude (typically 1 to 2 μm, peak to peak) is considered to be important in making consistent wire bonds but as yet no experiments have been completed in which tool tip amplitude has been correlated with such quality measures as pull strength or degree and appearance of deformation. However, after these procedures were incorporated by one semiconductor device manufacturer, a reduction by more than a factor of two was achieved in the rejection rate due to faulty bonds at visual inspection [71B5].

system Q

The Q of the mechanical system is an important consideration in the control of the bonding process. Normally, a broad or low-Q resonance is preferred so that drift of the oscillator frequency and changes in the temperature or loading do not significantly detune the mechanical system and reduce the ultrasonic power available to make the bond with a machine in the fixed-frequency, uncompensated mode. Kessler [70B3], has described a simple means of displaying the resonance curve of the tool displacement as a function of frequency on an oscilloscope screen.

power supply impedance

The Q and the resonant frequency have been found to be dependent on the output impedance of the power supply [70B3]. Measurements on the same transducer-coupler assembly and tool showed that the mechanical Q was lowest ($Q \simeq 70$) for a power supply with a constant current source, intermediate ($Q \simeq 135$) with a constant power source, and highest ($Q \simeq 200$) with a constant voltage source. The use of these different power supplies produced a maximum change in the resonant frequency of about 350 Hz.

temperature effects

Both resonant frequency and tool tip vibrational amplitude have been found to be dependent on temperature [70B2]. Temperature changes of five or more degrees Celsius may produce measurable changes in the operating characteristics of the bonder. For example, if high-intensity wide-angle lamps are used to illuminate the work area then appreciable heating (5 to 10°C) of the transducer-coupler assembly normally occurs. Thus

such bonding machines should be tuned after the lamps have been turned on for a time long enough to establish thermal equilibrium.

oscillator drift

To compensate for drift in the oscillator frequency and other changes that detune the mechanical resonance, a swept-frequency mode of operation has been used. Here the oscillator frequency is cycled repeatedly over a range which hopefully includes the mechanical resonance frequency. Feelings about this approach are mixed and no definitive evidence pro or con has been developed. A potential problem is that if the exciting frequency is sufficiently different from the mechanical resonant frequency, other vibration modes may be excited in which the tool tip moves in directions other than parallel with the wire and bonding surface. This may occur in some cases if the driving frequency is as little as 400 Hz different from the mechanical resonant frequency.*

frequency sweep

problems with frequency sweep

The primary advantage of using the swept-frequency mode of operation is that bonding should be relatively independent of the mechanical resonant frequency. However, Harman and Kessler [69B6], [70B3] have questioned this independence by showing that the variation of the tool tip vibration amplitude during the cycle is dependent on both the location of the mechanical resonant frequency within the range swept and the way the frequency is modulated because of the lag in the response of the mechanical system to rapid changes in the exciting frequency. It remains to be seen, however, whether the differences they noted are sufficient to result in significant changes in the quality of the wire bonds so fabricated.

slow sweep

A better case may be made for a single or several slow sweeps through resonance to make the bond [70B3]. If the frequency is modulated linearly and slowly enough to allow the mechanical system to respond, the dynamic response of the tip vibration amplitude envelope is similar to the static resonance curve. Under these conditions the initial coupling between the tool and wire, and the completion of the bond are accomplished under low-power conditions. Some believe that it is better to use a low power initially to avoid heating at the tool-wire interface because of possible slippage there, and to use low power at the end of the power cycle to reduce the possibility of inducing wire fatigue. Jones [67J1] has recommended the use of this kind of variation of power, but for larger work.

feedback

Other techniques to compensate for oscillator drift or changes in the loading conditions have been to use a feedback circuit [69U2] or to incorporate the transducer (piezoelectric) in the oscillator circuit itself. These techniques have been incorporated in a few commercially available bonding machines. The feedback circuit offers the opportunity of also being used to monitor the making of a bond and thereby evaluate each bond as it is made (see section 5.15).

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*M. Uthe, Uthe Technology, Inc., Sunnyvale California 94086, private communication.

4.6.4.3. Transducer and Coupler Assembly

transducer and coupler assembly

The transducer* converts the electrical oscillations from the power supply to mechanical vibrational motion which is transmitted along and amplified by a coupler assembly to whose end the bonding tool is fastened. The coupler is pivoted about a nodal point of the transducer-coupler assembly and the bonding force is applied through an adjustable dead weight or spring.

defective mount

If the mount for the assembly absorbs ultrasonic energy, power delivered to the bonding area is reduced and bonding is thereby affected. Harman [70B2] encountered such energy absorption in testing several mounts. By monitoring the tool tip vibration amplitude, different symptoms of such absorption were observed: absorption at a subharmonic frequency; small, irregular variations in the tool tip vibration amplitude; and a dependence of the mechanical resonant frequency on applied ultrasonic power. Such absorption was reduced by wrapping the mount screw threads with polytetrafluoroethylene plumbing type tape. This material is an excellent damping material for ultrasonic vibrations. Johannesen [71J1] has reported intermittent loss of ultrasonic energy in loose pivot bearings in the mount.

4.6.4.4. Bonding Tool

tool vibration

The bonding tool is fastened near to the end and anti-node of the coupler. The tool transmits the amplified vibration motion from the coupler to the wire and bonding surface. The direction of the motion of the tool tip is parallel to the bonding surface and the wire. Some early bonders used a perpendicular vibrational mode [67R2] but this is no longer in use because of the difficulties encountered in counter balancing the coupler assembly, transducer, and other attached accessories. Joshi [71J2] reported the use of vibration modes along each of three mutually perpendicular directions, one being in the direction of the wire being bonded. He claimed that the strongest bonds resulted when the tool vibration was in the direction of the wire.

vibration modes

The tool when energized with ultrasonic power from the coupler vibrates not as a rigid beam but as a flexible beam with nodes and anti-nodes. The relative vibrational amplitudes along tools of two principal lengths used are shown in figure 10. The tip of the tool oscillates thru a total distance of about 1 to 2 μm for typical bonding conditions [70B2], [71B1]. Because the bonding tool is an integral part of the ultrasonic system, the material, size, and position of the tool when installed have an effect on

vibrational amplitude

*Bradfield [70B5], [70B6] has provided some background material on various types of transducers and their applications.

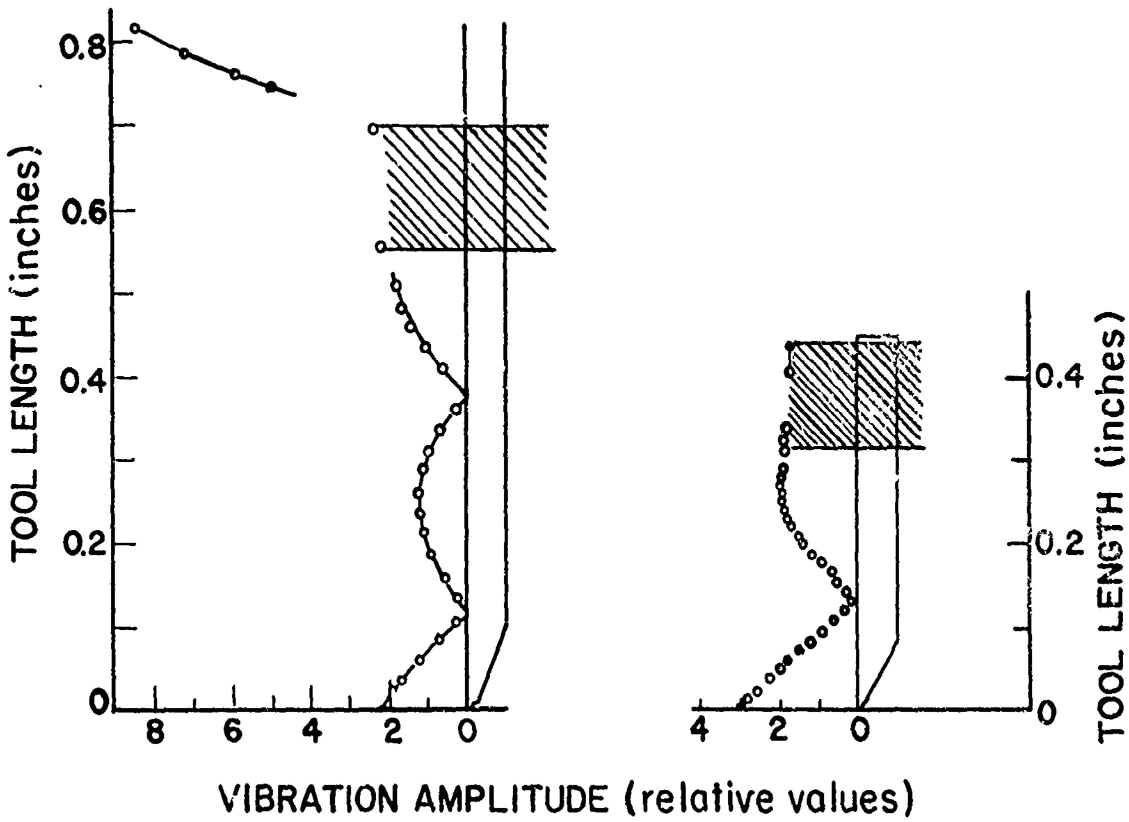


Figure 10. Typical vibrational amplitudes along a long and a short ultrasonic bonding tool at tool extensions recommended by the manufacturer. Data was taken with a high resolution capacitor microphone. The vibrational amplitude of the coupler (shaded) is also shown. Amplitudes are i relative values. The tool tip amplitude for typical bonding conditions is about from 1 to 2 μm. (From Harman [70B2], [70B3])

the operation of the system and hence the bonding operation. A given ultrasonic system operates best with tools of certain lengths installed with certain extensions below the coupler (tool extension). The effect of a change in tool extension of as little as 15 mils (0.38 mm) on the relative vibrational amplitude of the tool tip as measured by Harman [70B2] is shown in figure 11. The figure also illustrates the vibrational amplitude envelope along the length of the tool.

tool extension (effect of)

Both the mechanical Q of the ultrasonic system and the relative tool tip vibration amplitude may be affected by variations in the length of the bonding tool and its extension below the coupler, even for tools designed for the system [70B2], [70D2]. Significant changes in the tool tip vibration amplitude have even been seen when the tool is replaced with the same extension. This change was traced to the finish of the hole in the coupler, through which the tool is fitted; the set-screw used to hold the tool in place; and the torque used to tighten the set-screw. All appear to be able to affect the quality and position of the anchoring of the tool in the coupler which in turn affects the vibration amplitude of the tool tip [70B2].

tool anchoring (effect of)

Tools are most often made of tungsten carbide. The mechanical characteristics of tungsten carbide depend on the series of processes used in its fabrication. Accordingly, the performance of tungsten carbide tools in the ultrasonic system is affected by variations in the fabrication processes. These effects may be sufficiently significant to require changes in the bonding schedule when tools made from a different batch are used. Therefore it is prudent to keep separate tools made from different batches.*

mechanical characteristics (WC tools)

Tools are generally of wedge-type construction as shown in figure 12 with a wire-feed hole in the rear part of the tool through which the wire is fed by a wire-clamp assembly (shown in figure 9). In some cases, a capillary-type tool is used to make stitch-type ultrasonic bonds and (when gold wire is used) ultrasonic ball bonds. They are many designs for the wedge bonding tools. Some of the design considerations are the shape of the bonding surface, radii of curvature of the front and back bonding surface edges, bonding surface finish, length of the bonding face of the tool (foot length), and the size and location of the wire-feed hole. Optimization of tool design is difficult because of the lack of adequate knowledge about the effects of the various design features on the wire bond fabricated. Usually a subjective decision is made, based on experience, tradition, and some cursory experimental work.

tool design

figure 12

The bonding face is usually flat. Variations, primarily intended to minimize tool-to-wire slippage, include a groove perpendicular or parallel to the direction of the wire. A problem with having a groove parallel to

tool face and edges

*S. Bonis, Raytheon Corp., Sudbury, Mass. 01776, private communication.

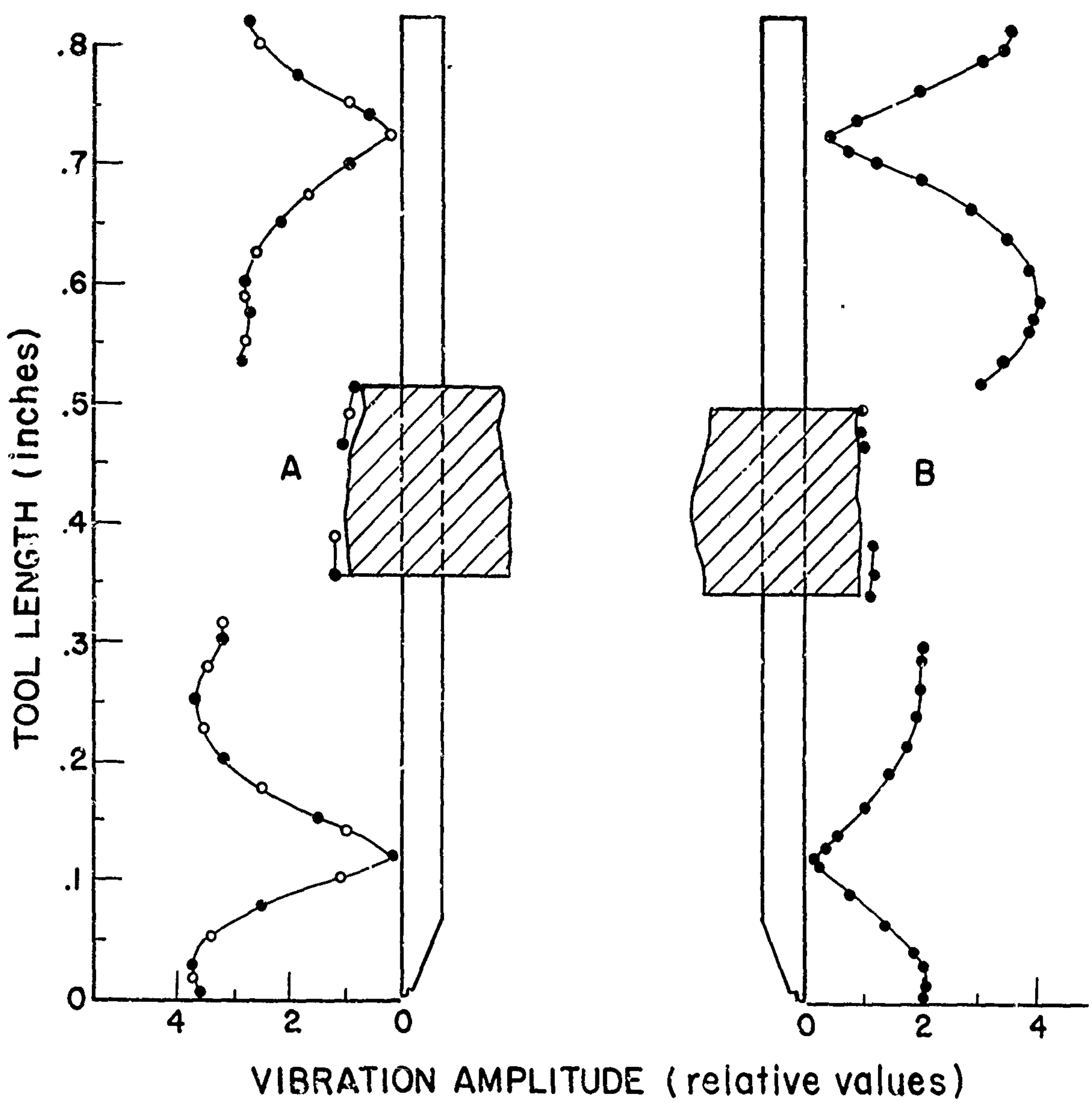


Figure 11. Vibrational amplitude along a long ultrasonic bonding tool for a tool extension of 0.350 in (0.889 cm), *A*, and a tool extension of 0.335 in (0.851 cm), *B*. The power setting on the power supply was the same for both extensions but the frequency was slightly different to achieve maximum amplitude in each case. Data were taken with a high-resolution capacitor microphone. Rounding of the amplitude envelope at the tool ends are attributed to edge effects. The vibrational amplitude of the end of the transducer coupler, which is generally less than that of the tool, is shown in the center part of the figure. Amplitudes are relative values. (From Harman [70B2])

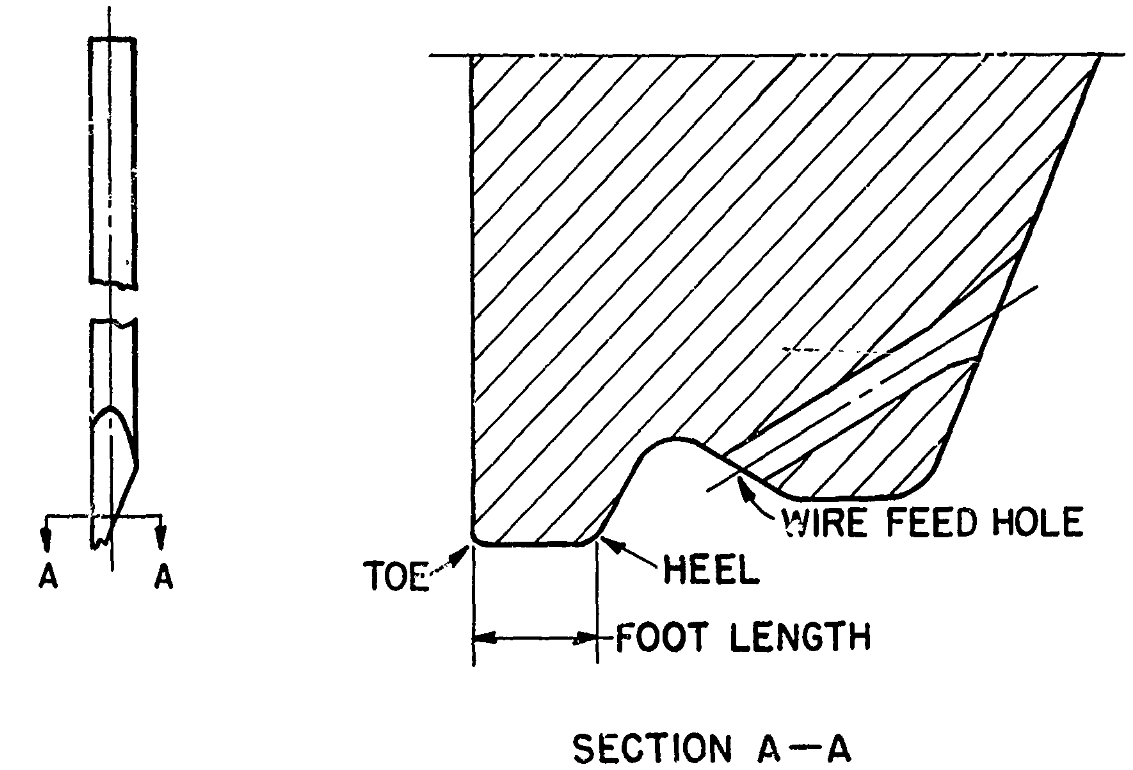


Figure 12. Sketches of the bonding end of an ultrasonic bonding tool.

the wire is the need to align the small diameter wire in the groove. To facilitate coupling between the tool and wire and to facilitate wire rupture after the second bond has been made, the back or heel of the tool has a relatively sharp edge. However, this edge cannot be too sharp or excessive deformation at the heel of the first bond can result.

surface finish

The surface finish of the bonding face of the tool is also of importance in preventing undue slippage between the wire and tool. To avoid inconsistent bonding characteristics due to such slippage, some have recommended that new tools be "broken-in" by making a few hundred bonds before using them on the production line. Plough *et al.* [69P1] have mentioned simply that the tool should have a rougher surface finish than the wire. Uthe [69U1] has suggested that a sign that a good bond has been made is that the part of the wire that had been in contact with the bonding tool should have a rough or granular texture, indicating that some bonding with the tool has occurred. Yet others claim that a smooth surface is important, with no break-in period recommended; otherwise the wire tends to stick to the tool and the bond is weakened when the tool is raised!

foot length

Use of tools with a short bonding face, or foot length, increases the change of inadvertently applying too much pressure to the semiconductor substrate and causing fracture. Also, Plough *et al.* [69P1] have reported that the power setting is more critical when using tools with a short

foot length and have recommended in agreement with Johannesen [71J1] the use of a tool with as long a foot length as the bonding area will allow. For 1-mil diameter wire, foot lengths of at least 75 to 100 μm are generally recommended.

wire-feed hole

The size of the wire-feed hole and its location relative to the bonding surface should be such that excessive rubbing of the wire against the tool is avoided as the wire is paid out in the process of moving from the first bond site to the second bond site [69P1]. Such rubbing tends to stress the heel of the first bond or to nick and scrape the wire. This problem can be reduced by moving the hole farther from the bonding face, but this introduces wire alignment problems.

4.6.4.5. Mechanical Stage for Transducer-Coupler Assembly

mechanical stage

The mechanical stage for the transducer-coupler assembly is usually cam operated to move the assembly and attached bonding tool in a vertical direction to either of two heights preselected to correspond to those of the die and of the terminal bonding surfaces of a particular package. In some machines the stage moves the assembly backwards automatically in the direction of the second bond site after the first bond has been made to make a controlled wire loop.

wire flexing

The very nature of the bonding sequence after making the first bond subjects the wire at the heel of the first bond to considerable flexing which can degrade the wire there [71G1] (see figure 7). Attempts have been made to moderate these stresses by moving the tool off the bond at an angle considerably less than 90°. Comments made privately indicate that these attempts have not been entirely successful.

tool tipping

With some machines, the stage can also tip the wedge tool forward a few degrees for the first bond to reduce the wire deformation at the heel of the bond. The tool may also be tipped backwards on the second bond to increase the wire deformation at the heel and thereby facilitate the break of the wire there, after the bond has been made. A possible objection to the use of these procedures is the increased sensitivity to minor misadjustments which because of the smaller effective bonding surface of the tool may apply excessive stress to the semiconductor substrate.

operation speed

During fast operation the tool and associated assembly may not follow the cams and as a result may vibrate or bounce. This can result in undesirable wire flexing. Such loss of control in tool movement is especially critical when the tool is lowered from the search height to the bonding surface.

tool drop

Variations in tool impact velocity lead to variations in wire deformation,* before the ultrasonic power is turned on, and inconsistent bonding. For

*The typical bonding forces used alone result in negligible wire deformation.

greater reliability Plough *et al.* [69P1], Davis [70D2], and Johannesen [71J1] have recommended the operation of the bonding machine be slowed if such problems are encountered. Johannesen [71J1] has recommended a tool drop velocity of 0.1 to 0.2 mils/ms (0.25 to 0.50 cm/s).* At greater velocities he noted inconsistent bonding.

tool drop

4.6.4.6. Chuck and Movable Stage for Device

chuck & movable stage

A chuck to hold the device package is part of a movable stage used for positioning the bonding sites beneath the bonding tool. Johannesen [71J1] has mentioned the difficulty in clamping the device package to attain the required rigidity. The problem is most severe with packages made of brittle materials because of the forces that must be applied.

package clamping

Extraneous relative displacements between the tool and bonding surface during bonding should be limited to significantly less than one-tenth the wire diameter [71H1]. Such movements can be induced by a variety of sources such as building vibrations, nearby machinery, and inadvertent bumping. It was reported that relative movements of 25 μm or more could be induced in one bonding machine by only a slight movement of the hand while in contact with the movable work stage holding the device. This stage was designed to be rotated manually and the operator's hand would normally be in contact with it during bonding [70B3]. In another experiment it was found that when low-frequency vibrations of the bonding surface with an amplitude of about 25 μm relative to the tool were induced during bonding, more than half the bonding attempts were unsuccessful, either because of no bond adherence or because of wire breakage [70B7].

extraneous movement

4.6.4.7. Wire Clamps

wire clamp (use of)

The basic purpose of the wire clamp is to contact the wire and to feed the wire forward under the wedge tool in preparation for making the first bond and to pull back on the wire to break the wire at the heel of the second bond.

Koshinz [67K1] mentioned the problem with the operation of some wire clamps which because of their abrupt movements could cause mechanical transients in the wire. Laub and Mansour [69L2] describe a design which is intended to eliminate this problem. Leedy [70B3] reported that poorly finished wire clamps could make indentations on the sides of the wire resulting in work-hardening the wire and also embedment of contaminants in the wire at these points. The latter is particularly important if the wire twists so that the indented parts of the wire face the surface when the wire is bonded.

problems

*The text of [71J1] gives values of 1.0 to 2.0 × 10^{-4} mils/ms which is a typographical error (private communication with William Meyle, who presented the paper for Johannesen).

5. METHODS FOR TESTING AND EVALUATING WIRE BONDS

5.1. Introduction

test methods

Methods used to test and evaluate wire bonds are described. To serve as a quick reference for the reader, the methods are listed with brief, descriptive phrases in table 3. Some methods are used to test only the wire bond while others also stress other components of the device and package as well. The latter fall in an environmental or environmental-simulation test category. In general, the methods are intended to perform one or more of four functions: (1) to optimize the process for making the wire bond, (2) to determine if this process remains in control, (3) to obtain a measure of the quality of the wire bond, and (4) to cull out those wire bonds that will fail under normal operational stress.

use of methods

test conditions

MIL-STD-883

Where such information is available, the range of values for the test conditions specified in standards and reported in the literature are tabulated with the description of the method. MIL-STD-883 [68D2], [69D3], [6901] has been influential to the extent that most of the test specifications quoted in the literature are essentially identical to those of this military standard. This is understandable considering that MIL-STD-883 was in part an outgrowth of test practices in the industry [69B8] and because of clear evolutionary links with the earlier (now revised) MIL-STD-750B [70D3] and MIL-STD-202C [63D1], which in turn had widespread use. Additional influence has been provided MIL-STD-883 by adoption of these test specifications by NASA as part of its microcircuit line certification requirements [71N1] and in the purchase of its microcircuits [69D3].

discussion

analysis

Also, each method is discussed in terms of its potential effectiveness and practicality. These discussions include comments made in the literature and general experience as related in interviews. Analyses of some of the methods with regard to the stress that the test imposes on the wire bond have been made and the results are used in the discussions of the relevant methods.

correlation

Relatively little information has been found regarding the results of testing the correlation between different test methods for the same type of wire bond. What has been found is included in section 5.16.

Table 3 - Test Methods and Brief Descriptions

Air Blast (5.5)	— A jet of gas is directed at the wire.
Bond Monitoring (5.15)	— Some measure of the mechanical coupling between the tool, wire, and metal film is monitored during ultrasonic bonding.
Bond Interface Resistance (5.14.2)	— The contact or bond-interface resistance is measured by a four-probe method.
Centrifuge (5.5)	— A constant centrifugal force is applied to the device.
Electrical Continuity (5.14.3)	— A small current through the bond is used to test for electrical continuity.
Mechanical Shock (5.9)	— A large, short-duration deceleration is applied to the device.
Noise Measurement (5.14.4)	— Noise is used as an indicator of contact abnormalities.
Pull (5.3)	— Tensile forces produced by pulling the wire by some means are used to stress the wire bond either to some predetermined tensile stress or to destruction.
Push (5.6)	— A probe is used to apply a deflecting force to the wire in a direction perpendicular to the plane of the wire and bonds.
Short-Duration Stress (5.12)	— The absorption of a short pulse of high-energy electrons is used to produce thermally-induced tensile stress waves in the device.
Shear (5.4)	— A probe, applied to the deformed wire above the bond interface, is used to apply a shearing force at the bond interface.
Temperature Cycling and Thermal Shock (5.13)	— The device is exposed alternately to two temperature extremes.
Ultrasonic Stress (5.9)	— Ultrasonic waves in a liquid medium are directed at the device.
Variable Frequency Vibration (5.10)	— The device is vibrated through some frequency range at a relatively constant, maximum acceleration.
Vibration Fatigue (5.11)	— The device is vibrated at a fixed frequency for a long period of time and at a relatively small maximum acceleration.
Visual Inspection (5.2)	— The wire bond is examined to determine if it conforms to predetermined criteria of physical appearance and location.

visual inspection

5.2. Visual Inspection

5.2.1. Description

widely used

Visual inspection of the pre-encapsulated device is one of the most widely used methods for evaluating wire bonds, as well as other parts of a device, such as its metallization. The examination of the wire bond is usually performed with the use of a microscope under specified magnification within the range of 30 X to 100 X and usually at specified angles of observation and lighting.

test philosophies

There have been two underlying philosophies in the selection of criteria for visual inspection tests. One contains a greater reliance on (or expectation of) the test to detect the more subtle potential reliability problems as well as the gross defects. Consequently, the criteria of acceptance are more detailed and more cosmetically orientated. The other embodies a greater acceptance of the limitations of the test so the criteria are selected to cull out only the more obvious defects [66P1]. This approach is the more attractive from the point of view of testing efficiency and economics.

table 4

Four visual inspection tests including those of MIL-STD-883, are outlined in table 4 and represent varying responses to these points of view. The higher the reliability required, the greater is the effort to use the test to detect the more subtle potential problems. However, for the chance of achieving greater reliability, the costs of reduced yield and additional testing time and labor must be paid. Flexibility in terms of the reliability sought is built into the visual inspection test of MIL-STD-883 [68D2]. Two levels or conditions A and B of the test are available to suit the reliability need. NASA has adopted the modern version of the MID-STD-883 visual inspection test except that a greater magnification of 80 X is used [71N1].

reject criteria

The visual inspection tests outlined in table 4 are each divided into three categories of reject criteria: bond placement, condition of the bond, and condition of the wire. The comments in the paragraphs to follow related to these criteria are meant to supplement the material in table 4.

bond placement

The bond placement specifications generally consider two potential placement problems: One is concerned with the possibility of short-circuits between adjacent bonds and between bonds and nearby metallizations. The other is concerned with adhesion of bonds placed partially off the bonding surface. Additional restrictions may be added to keep the bond on the die from being located too close to the exit metallization stripe. The reason for this restriction is that the bond can hide flaws or scratches such as produced by wafer probing which may have excessively reduced the conduction path in the stripe area [6901].

bonded wire

The specifications for the condition of the bonded wire relate mainly to the deformation of the wire at the bond and the bond contact area. The

rationale for allowing some reduction in the normal bond area is that the strength of the bond between the wire and metallization is generally much greater than the tensile strength of the most deformed part of the wire. The purpose of the deformation specifications is primarily to cull out bonds which have been over- or under-bonded. A reason a maximum length for wedge or stitch bonds is specified is to cull out bonds where significant relative parallel motion between the tool and bonding surface occurred while the tool was in positive contact with the wire. The width of the bond and any variation in it from bond to bond gives an indication of the degree and uniformity of the bonding force. Variation in width of a given bond may indicate misalignment of the tool relative to the bonding surface or wire. Inspecting the height of the bonded wire is another way of determining whether the deformation is within satisfactory limits and if any part of the wire has been excessively deformed. To inspect the bond height, the device must be viewed at an angle.

wire condition

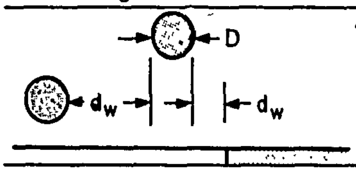
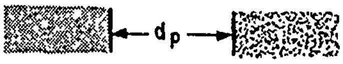
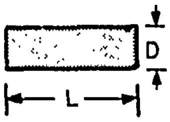
The specification for the condition of the wire relates to the location of the wire relative to other parts of the device, the length of the wire tail, reductions of the cross-sectional area or diameter of the wire, and sharp bends in the wire. A maximum tail length is often specified for wedge and stitch bonds. The tail length on the terminal is usually allowed to be longer than the one on the die, where spatial tolerances are more critical. Too long a tail is undesirable because of the possibility of its moving or even rupturing during a mechanical stress and thereby causing a short-circuit Moreover, an excessively long tail would imply poor wire-feed control or a large elongation for the wire which, as discussed in section 4.2, would also be undesirable. The criteria for excessive reduction of the cross-sectional area in the wire adjacent to the bond or at any nicks, scratches or flaws are usually given in terms of a maximum allowed reduction in the wire diameter but ocassionally they are given in terms of cross-section area which is more difficult to judge. An indicator of possible overstress in the wire adjacent to wedge and stitch bonds is a deviation, as viewed from above, of the wire span from a straight line connecting the two bond sites. Thus a maximum permissible deviation is sometimes specified.

SEM & x ray methods

There are other methods,* besides using an optical microscope, to evaluate wire bonds from an examination of their external appearance. The remaining paragraphs are devoted to the use of a scanning electron microscope (SEM) and the use of x rays for this purpose.

*The recently introduced intensity spatial filtering technique [69W1], [69W2] is not applicable for wire bonds, however. Its use for detecting flaws in photomasks has been detailed and its use for screening complex metallization patterns is indicated. However, the relative lack of regularity in regard to the placement, shape, and routing of wire bonds as well as the fact that they are not all in the same plane precludes the use of this technique.

Table 4 - Visual Inspection Reject Criteria for Condition of Wire, Condition of Bonded Wire, and Placement of Bond

CONDITION of WIRE	REJECT CRITERIA				
	MIL-STD-883 Method 2010.1		66L4	66P1	68R1
	Condition A	Condition B			
Magnification	30-50	30-50	50	20	~30
 *	$d_w<2D$ †	$d_w \leq 0$ †	$d_w \leq 0$	$d_w \leq 0$	$d_w \leq 0$
	$d_p<2D$ †	$d_p<\varepsilon$ †	$d_p<3$ mils $d_p<\varepsilon$	$d_p<\varepsilon$	$d_p \leq 1$ mil
	die L>2D terminal L>4D	die L>2D terminal L>4D	L>2 mils	L>2D	——
	$D_m<3/4D$	$D_m<3/4D$	$D_m \leq 3/4D$	$D_m<3/4D$ § $D_m<1/2D$ ×	$D_m<2/3D$
TEAR 	yes	yes	——	——	——
	——	——	——	——	R<2D

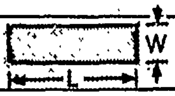
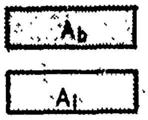
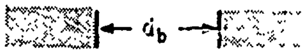
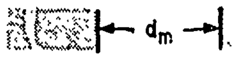
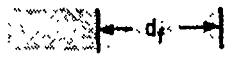
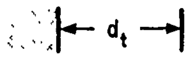
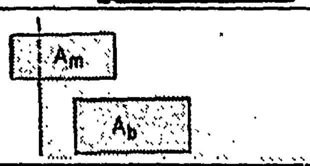
CONDITION of BONDED WIRE	REJECT CRITERIA				
	MIL-STD-883 Method 2010.1		66L4	66P1	68R1
	Condition A	Condition B			
Magnification	30-50	30-50	50	—	~30
	W<2D; 6D<W	W<2D; 6D<W	——	——	W<2D; 5D<W
	W<1.2D; 3D<W L<1.5D; 5D<W	W<1.2D; 3D<W L<1.5D; 5D<W	——	——	——
	$A_b<1/2A_i$	——	$A_b<A_i$	——	——
Rebonding on Die	yes	no	yes	——	sometimes
Rebonding on Terminal	no	no	yes	——	——

Table 4 - (Continued)

PLACEMENT of BOND	REJECT CRITERIA				
	MIL-STD-883 Method 2010.1		66L4	66P1	68R1
	Condition A	Condition B			
Magnification	30-50	30-50	50	20	~30
	d_b<1/4 mil	d_b<1/10 mil	——	——	d_b<1/4 mil
	d_m<1/4 mil	d_m<1/10 mil	——	——	d_m<1/4 mil
	d_f<1/2 W_f+	d_f<1/10 mil+	d_f<2 mils¶	d_f<4/10 mil	——
	——	——	d_d<1 mil	——	d_d≤1/10 mil#
	d_t≤0	d_t≤0	——	——	——
	d_w≤0	d_w≤0	——	d_w<0	d_w<0
	die^α^ A_m<3/4A_b terminal A_m<A_b	die A_m<1/2A_b terminal A_m<A_b	——	die A_m<3/4A_b ** A_m<1/2A_b ††	die A_m<2/3A_b ** A_m<1/2A_b §§

Symbols

wire

metallization

other parts of device or package

non-contacting area

edge of die

Notes

* vertical view

† wire at a distance greater than 10 mils from its termination

§ at a magnification of 80 X

× if adjacent wedge bond to terminal

+ to farther edge of interconnecting metallization stripe of width W_f

¶ also if bond is in interconnection metallization stripe

actually, if no separating oxide is visible

α A_m < A_b for hybrid circuits

** for wedge bonds

†† for ball or stitch bonds

§§ for ball bonds

Notations

A_b - bond area

A_i - bond-impression area

A_m - bond area over metallization

D - wire diameter.

D_m - minimum thickness at deformation in wire

d_b - distance between bonds

d_d - distance from bond to die edge

d_f - distance from bond to farther edge of interconnection metallization stripe

d_m - distance from bond to adjacent metallization

d_p - distance from wire to any part other than metallization or another wire

d_t - distance of bond tail to adjacent metallization

d_w - distance from wire to another wire or to metallization, as seen from a vertical view

c - smallest distance at which wire will not touch other parts, if stressed

L - length of bonded wire or of bond tail

R - radius of curvature of bend in wire

W - width or diameter of bonded wire

W_f - width of metallization stripe from bonding area

SEI

Although the SEM has been used extensively in the failure analysis of wire bonds its use, on a sampling basis, has only recently been introduced in the NASA microcircuit line certification requirements [71N1]. The use of the SEM in a screen test for wire bonds would be a powerful but a rather slow tool to use. One problem with its use is the possible degradation of the electrical characteristics of devices so examined [68O1]. No degradation effects are expected with use of a scanning electron mirror microscope [69C2]. However this technique is still in the development stage.

x ray

X-ray examinations are used to detect defects in encapsulated devices [68D2]. With reference to wire bonds they are primarily used to view the orientation of gold wire to see if the fabrication procedures subsequent to pre-encapsulated visual inspection or any previous test stresses have resulted in changes in the wire orientation which could constitute a potential reliability problem. The use of an x-ray vidicon for this purpose has been judged to be a highly valuable screening test for devices with gold wire [66L4]. Because of the relative transparency of aluminum to x rays, however, this technique is not useful for devices with aluminum wire bonds [66L4], [68H4].

5.2.2. Discussion

discussion

limitations

While visual inspection is widely used it is most effective when used in conjunction with other tests. It cannot be expected to cull out all weak or defective wire bonds even if performed perfectly [69O1], [69P1], [69S4]. It is used successfully to detect relatively gross visual defects but its success in detecting the more subtle defects is mixed [69S1]. In attempts to do so it is also apt to be overly critical and reject acceptable wire bonds, thereby needlessly reducing the yield.

criteria relevance

There are at least three basic limitations to the visual inspection test. Firstly, the criteria in present visual inspection tests have not been fully documented as to their relevance to the reliability of the wire bond. These criteria are, essentially, an outgrowth of past experience, common sense, and sometimes even guess. For example, in one instance when questioned for the reason for a criterion for an acceptable bond deformation that should be allowed, the answer was that it was an educated guess.

subjectivity

Secondly, the test is subjective and suffers from human error. The more complex the product and the criteria, the less effective the inspector [68H1]. It has been estimated that a visual inspection test performed by a single operator is only about 80 percent effective. Thus, even if two non-correlative redundant tests* were performed then only 96 percent of the possible defects would be detected. This is far from the kind of effectiveness

*The implementation of such tests is no small problem because of psychological considerations.

required to detect one defective wire bond in 10,000 which for a 14-lead device represents one device failure in about 700.

Thirdly, some defective wire bonds cannot be detected by visual means. The wire may be deformed as desired yet have essentially no adherence to the bonding surface. This might occur, for example, because of surface contamination, poorly adhering metallization, or, for thermocompression bonds, too low a bonding temperature. The process of bonding may result in a fracture of the semiconductor material under the bond yet the wire deformation at the bond site may not appear unusual.

detectability

As a precautionary note it should be added that some of the criteria may be expected to be dependent on the type of wire used. For example, the acceptable range of wire deformation may be dependent on the hardness of the wire as well as its nominal diameter. Implicit in most visual inspection tests is that 1 mil diameter wire is used. However, 1.5 mil and 0.7 mil diameter wires are also in use. For 1.5 mil diameter wire, a wire deformation equal to or only slightly larger than the nominal wire diameter has been found to be satisfactory while such a deformation would be inadequate for 1 mil diameter wire. More work along the lines initiated by Kashiwabara *et al.* [69K1] is needed to clarify the effects of these and other variables on the strength of the wire bond and on an appropriate range of bond deformations.

precautionary note

5.3. Pull Test

pull test

5.3.1. Description

In its basic form, the pull test consists of pulling on the wire span by some means (usually with a hook) with increasing force until either a predetermined force is applied or a rupture in the wire bond occurs. In the latter case, the test is destructive; the pulling force required to produce rupture is called the pull strength and it is used as a measure of quality for the wire bond. In the former case, the test is meant to be nondegrading as well as nondestructive to satisfactory wire bonds but destructive to the rest. A variation of the destructive pull test is to cut the wire somewhere along its span and then pull one of the wires at some angle with respect to the bonding surface and measure the force at which a rupture occurs. In some cases only one bond is made and tested. When only one bond is involved, the test is called a single-bond pull test and the pull strength is equal to the tensile force in the wire. When two bonds are involved, it is called a double-bond pull test and the pull strength is generally not equal to the tensile forces in the wire. Test specifications listed in table 5 summarize the extent to which the conditions of the pull test are specified.

pull strength

single-bond pull

double-bond pull

The pull test is used to (1) develop the bonding schedule by varying the bonding machine parameters until acceptable pulling forces are attained,

uses of method

(2) maintain control of the bonding process by periodically testing samples of wire bonds that are produced, (3) determine the effect of other processes or stresses on the wire bond by monitoring pulling forces of representative samples, or (4) cull out weak wire bonds either by sampling a group which is accepted or rejected on the basis of the performance of the sample, or by a 100 percent nondestructive test.

data analysis

In the destructive pull test the pull strengths of a sample are taken to be representative of the group. The pull strength is recorded and, usually, the location of the rupture as well. The pull strength is often expressed in grams, although a grams-force unit is implied. To facilitate the analysis of the data, the distribution of pull strengths can be displayed in a histogram. The magnitude of the pulling force at the peak in the distribution displayed in the histogram gives an indication of the general ruggedness of the wire bond while the spread of the distribution indicates the uniformity of a group, how well the fabrication processes are under control, and how uniform are the constituent materials.

failure modes

The failure mode, or location of rupture, reveals the weakest point in the wire bond for the kind of stress imposed. The most common point of rupture is in the wire adjacent to one of the bonds, because of the reduced cross-sectional area or mechanical strength there. Thus, the pull test is

Table 5 - Pull Test Specifications and Conditions

Source	Gauge Accuracy	Rate of Pull	Probe Material	Diameter of Wire Probe
71N2*	±0.5 gf for 0-10 gf ±1.0 gf for 0-100 gf	"slowly"	steel, tungsten	5 mil (0.13 mm)
71B4	—	1.0-77 gf/s	—	—
70A1	±0.05 gf (load cell)	—	molybdenum	5 mil (0.13 mm)
69K1	—	2 mm/min	—	—
69B5	—	—	—	2 mil (0.05 mm)
68D2	+0, -0.5 gf for 0-10 gf +0, -1.0 gf for 10-50 gf	—	—	—
67S3	—	0.77 mm/min	—	—
67H1	—	"slowly"	—	—
66R1	—	0.2-0.5 in/min (0.13-0.5 mm/min)	—	—

*Test is performed under a microscope at a magnification of 45 X.

more a test of the deformation of the wire than a test of bond adherance, as has been pointed out by Howell and Kanz [65H2], and others. If the rupture occurs at the point of contact of the wire with the probe (usually a hook) then the probe itself may be damaging the wire and invalidating the test. This is most apt to occur after high temperature stress which has annealed the wire.

pulling element

The great majority of pull tests use a hook fabricated from a wire, typically tungsten, to pull on the wire span. The other end of the wire is attached to a gauge to measure the applied force. The wire diameter at the hook is typically between 40 to 80 μm (1.5 to 3.0 mil) and a primary concern is that the hook not damage the wire during the test. In cases where it is felt that the height of the wire span is insufficient to position a suitable hook, an "L" shaped probe or a pointed, straight-wire probe has been used.

rate of pull

The rate of pull is a parameter that is occasionally specified for the pull test. It is given either in terms of the speed of the pulling element [66R1], [67S3], [69K1], or the rate of increase of the force, as measured at the pulling element [70B8]. In some pull tests, the only specification is that the force must be applied "slowly" [67H1], [71N2].

testing machines

Test apparatus for making both destructive and nondestructive pull tests is commercially available. A design for incorporating a nondestructive pull test in a bonding machine making special "eyelet" thermocompression bonds was reported by Baker and Jones [66B4]. At the time of the report, a prototype wire-feed in which the wire is retracted by rotating the wire spool had been constructed for 2-mil diameter aluminum wire. Nothing since has been seen in the literature about any further development or use of this design. Present-day bonding machines do not feature it.

single-bond pull

The purpose of a single-bond pull test is usually to better control the angle of pull (with respect to the bond and contact surface) and also thereby minimize flexing and hence weakening the deformed wire adjacent to the bond. In the case of a completed wire bond, the wire is severed somewhere along its span and one half of the wire bond is tested. However, a means of gripping the wire is required in this test.

gripping wire

Wasson [65W1] has described the use of special tweezers to grip the wire. Adams and Anderson [68A1] have recommended the use of a black wax. A separate heating element is used to liquify the wax at the end of a probe which engulfs the wire by capillary action. They report that the tensile strength of the wax is sufficient to measure pull strengths up to 150 grams-force. More recently, Harman [69B5] has described the use of high-tensile-strength hot-melt glues, with discrete melting-points, at the tip of a nichrome wire-loop probe. The glue is melted by passing current through the wire loop which has been electrolytically thinned so that most of the joule heating will occur there. The tensile strength and adherence of these glues are sufficient to test

1-mil diameter aluminum wire if about 0.13 mm length of the wire is bonded with the glue. The glues do not bond as well to gold wire so that a longer length of gold wire must be immersed in the glue.

grip stress

The use of wax or glue minimizes the grip-stress on the wire. Such stress is greater for a mechanical grip (by tweezers for example). Yet, while the grip-stress may be larger, Dudderar [69D1] indicated that the rapid strain hardening minimizes its effect and thereby serves to avoid wire rupture near the region of mechanical contact.

analysis

5.3.2. Analysis

purpose

This analysis is intended to provide relationships between the pull strengths and the actual force in the wire which can result in rupture and thereby also indicate the sensitivity of the test to the parameters of the test.

resolution of forces

By resolving the forces* in the pull test as shown in figure 13, the applied pull force, F, is related to the wire tensile force on the terminal side, F_{wt}, by

$$F_{wt} = F \times \frac{\cos(\theta_d - \phi)}{\sin(\theta_d + \theta_t)} \tag{5.3.1}$$

and to the wire tensile force on the die side, F_{wd}, by

$$F_{wd} = F \times \frac{\cos(\theta_t + \phi)}{\sin(\theta_t + \theta_d)} . \tag{5.3.2}$$

The angles θ_t and θ_d are the angles that the wire makes with the bonding surfaces of the terminal and die, respectively. The pulling probe is inclined at an angle ϕ with respect to a normal to the bonding surfaces. The case where the direction of pull is at some angle from the plane of the loop is not included in the analysis.

θ dependence

figure 14

The wire tensile force on the terminal side of the hook is greater than the applied force at the hook if $2\theta_d + \theta_t - \phi < 90$ deg. The ratio F_{wt}/F as a function of θ_t is given in figure 14 for various fixed ratios of θ_d/θ_t and for $\phi = 0$. The ratio F_{wd}/F as a function of θ_d may be obtain by interchanging the subscripts d and t. These curves indicate how dramatically the tensile force in the wire may differ from the force applied by the hook. Wire bonds with different contact angles may have entirely different tensile forces in the wire for the same pulling force applied at the hook.

*Similar equations have appeared earlier [70B7]. Equivalent expressions for $\phi = 0$ have been derived by Donald J. Manus, Texas Instruments, private communication.

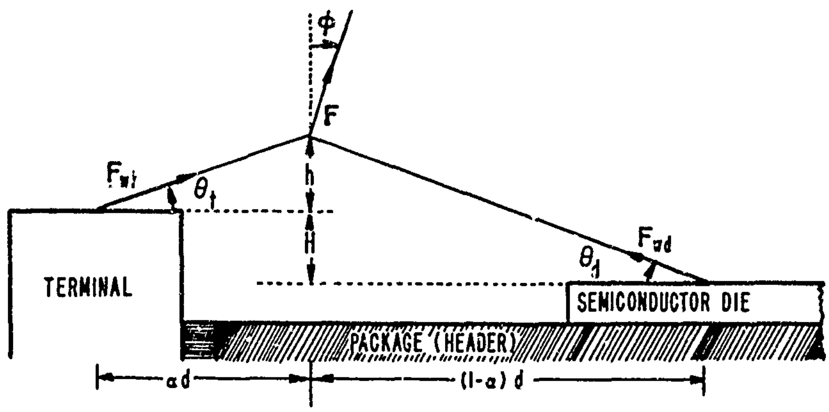


Figure 13. Geometric variables for the double-bond pull test.

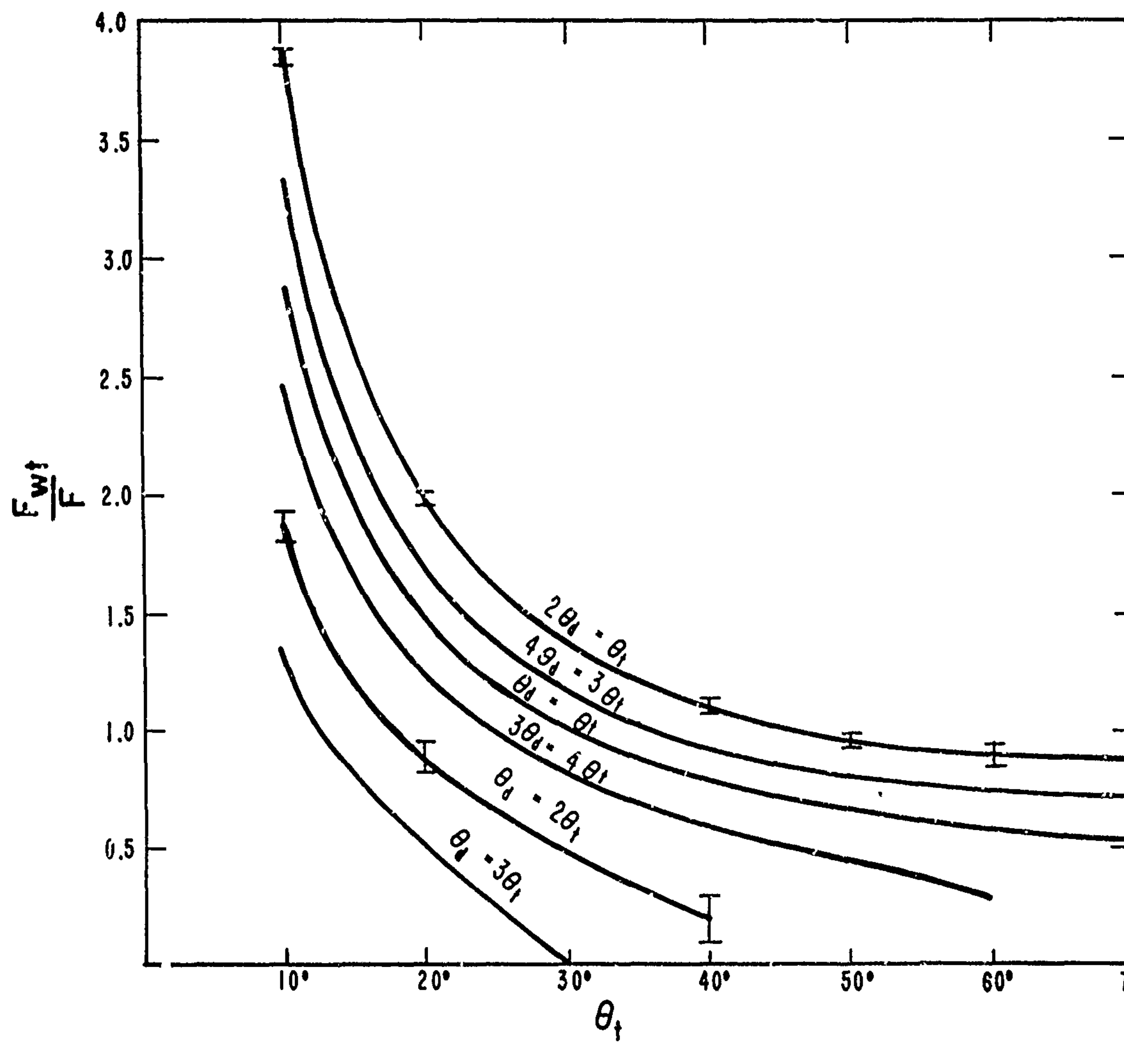


Figure 14. Dependence of F_{wt}/F on θ_t for various ratios θ_d to θ_t. The curves are for the case $\phi = 0$. Horizontal bars above and below the curves for $2\theta_d = \theta_t$ and $\theta_d = 2\theta_t$ show the effect of changing ϕ to plus and minus 5 deg, respectively. To obtain the dependence of F_{wt}/F, interchange everywhere the subscripts d and t and change the sign of ϕ.

ϕ dependence

The dependence of F_{wt}/F on the magnitude of ϕ is also indicated in figure 14. The effect of varying ϕ by ± 5 deg is shown by the horizontal bars on either side of the curves for $\theta_d/\theta_t \approx 1/2$ and 2. Positive values of ϕ result in a larger F_{wt}. The dependence of F_{wt} on ϕ increases with the ratio $\sin(\theta_d - \phi)/\sin(\theta_t + \theta_d)$. The symmetry between F_{wt} and F_{wd} is maintained if the sign of ϕ is reversed with the interchange of the subscripts d and t.

F_{wt}/F_{wd}

The ratio of the wire tensile force at the terminal side to that at the die side of the probe is given by

$$\frac{F_{wt}}{F_{wd}} = \frac{\cos(\theta_d - \phi)}{\cos(\theta_t + \phi)} \qquad (5.3.3)$$

Because the terminal bonding surface is usually higher than the die, θ_t is usually less than θ_d, and in this case, the tensile force in the wire is greater on the die side of the probe than on the terminal side.

h, H, α, d dependence

Although the geometrical dependence is more easily visualized in terms of the contact angles, these angles are difficult to measure in practice. The contact angles depend on the height, h, of the wire span above the terminal contact surface, the height difference, H, between the die and terminal contact surfaces, and the horizontal distances αd and $(1 - \alpha)d$, from the bonds to the point at which the wire span is contacted by the pulling probe. These quantities are shown in figure 13. Expressing equations (5.3.1) and (5.3.2) in terms of these quantities we have

$$F_{wt} = F\left\{\frac{\sqrt{1 + \left(\frac{\alpha d}{h}\right)^2}\left[(1 - \alpha)\cos\phi + \left(\frac{h + H}{d}\right)\sin\phi\right]}{1 + \frac{\alpha H}{h}}\right\} \text{ and} \qquad (5.3.4)$$

$$F_{wd} = F\left\{\frac{\sqrt{1 + \frac{(1 - \alpha)^2 d^2}{(h + H)^2}}\left(1 + \frac{H}{h}\right)\left[\alpha\cos\phi - \frac{h}{d}\sin\phi\right]}{1 + \frac{\alpha H}{h}}\right\}. \qquad (5.3.5)$$

For a pulling force normal to the bonding surfaces ($\phi = 0$), these equations simplify to:

$$F_{wt} = F\left\{\frac{(1 - \alpha)}{1 + \frac{\alpha H}{h}} \times \sqrt{1 + \left(\frac{\alpha d}{h}\right)^2}\right\} \text{ and;} \qquad (5.3.6)$$

$$F_{wd} = F\left\{\frac{\alpha\left[1 + \frac{H}{h}\right]}{1 + \frac{\alpha H}{h}}\sqrt{1 + \frac{(1-\alpha)^2 d^2}{(h+H)^2}}\right\}. \qquad (5.3.7)$$

For a pulling force applied at mid-span and normal to a single-level bonding surface ($\phi = 0$, $H = 0$, and $\alpha = 1/2$) these equations simplify further to:

$$F_w = F_{wt} = F_{wd} = \frac{F}{2}\sqrt{1 + (d/2h)^2}\,. \qquad (5.3.8)$$

experimental confirmation

Work is underway to confirm experimentally the dependence of pull strength on the geometry of the wire bond which is given by the above equations [71B1], [71B4], [72B1], [72B2].

figures 15, 16

Figures 15 and 16 have been provided to assist in the practical use of the relationships given in equations (5.3.6) thru (5.3.8). In figure 15 the ratios F/F_w and F_w/F as functions of d/h are graphed for a single-level (H = 0), double-bond pull test where the pulling probe is located at mid-span. The ratios F_{wt}/F and F_{wd}/F as functions of d/h for different values of H/h are graphed in figures 16a and 16b, respectively. Note that here the probe is located at a distance of one-fourth the bond separation from the bond on the terminal which is a rough estimate of where the apex of the wire loop would be and where the probe would normally be located in a two-level, double-bond pull test.

F/F_w; F_w/F

sensitivity to variance

To use the pull test in evaluating the control of the bonding process or the effect of factors which alter the strength of the wire bond, it is desirable to know the sensitivity of the pull strength to changes in the test variables, assuming that the wire tensile force necessary to cause rupture is constant and the failure mode does not change. With this information one may determine the extent to which the distribution of pull strength observed is actually due to variations in the quality of the wire bonds being tested. In selecting a particular configuration for the wire bond, it may be possible to select a configuration in which the sensitivity of the pull strength to those variables which can be least controlled in making a series of bonds is minimized.

ΔF

The measure used here to describe this sensitivity is the normalized variation in the pull strength, ΔF, where it is assumed that the tensile force in the wire to rupture the wire bond is unaltered by variations in the geometrical variables of the wire bond and the test.

$$\Delta F = \frac{F_1 - F}{F} \qquad (5.3.9)$$

where F represents the pull strength obtained when each of these variables has a selected value and F_1 represents the pull strength obtained when the

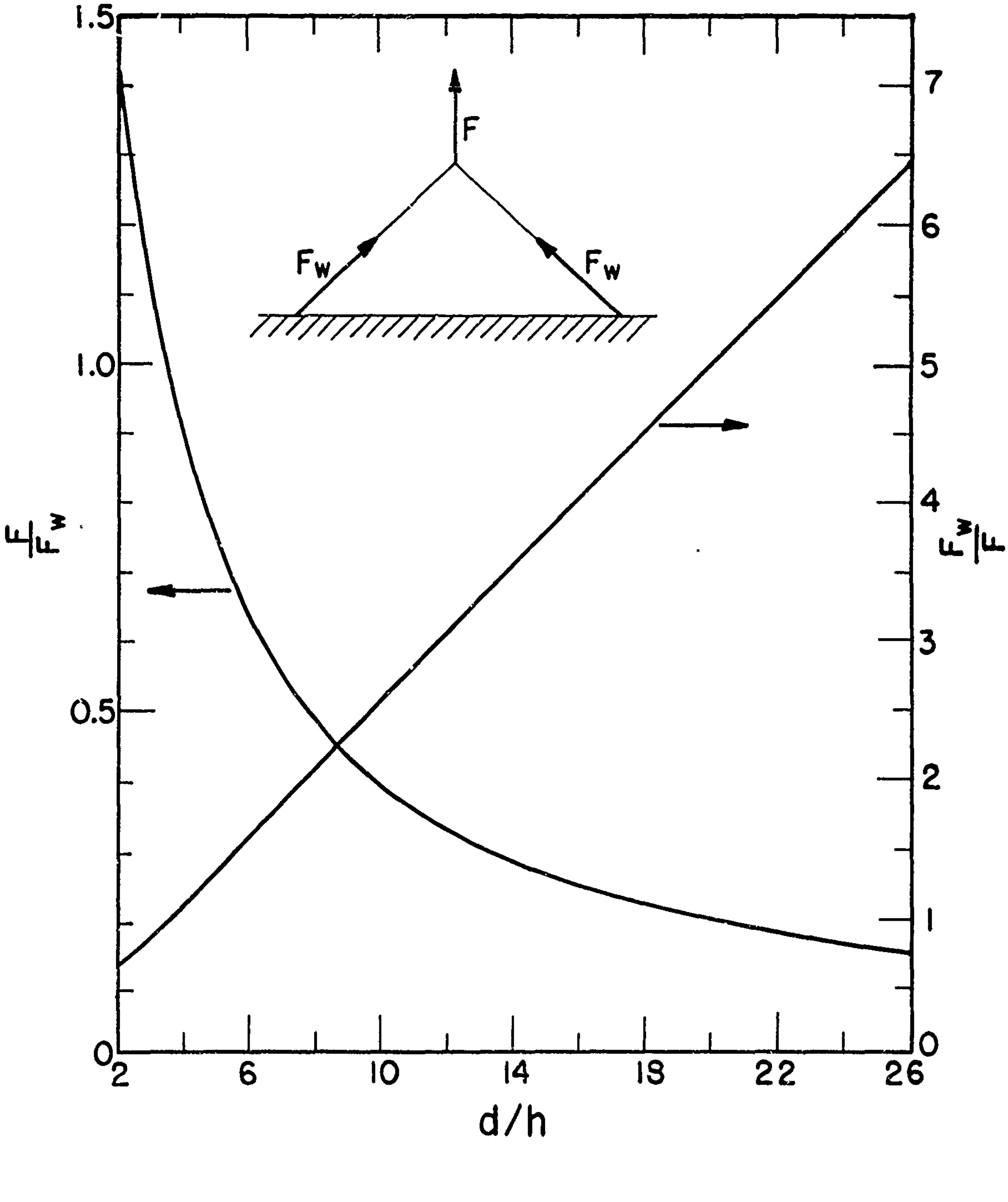


Figure 15. F/F_w and F_w/F as functions of d/h are graphed, for a single-level, double-bond pull test.

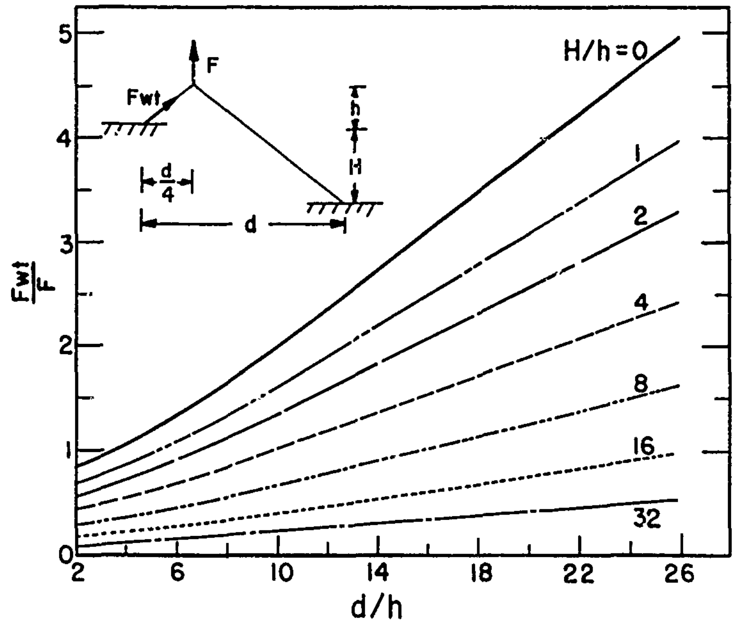


Figure 16a. F_{wt}/F as a function of d/h for different values of H/h and for $\alpha = 1/4$ is graphed, for a two-level, double-bond pull test.

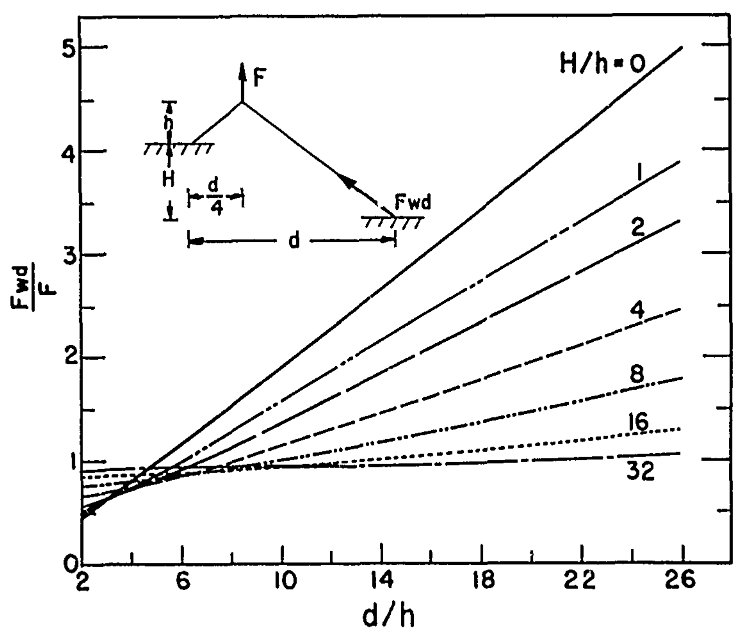


Figure 16b. F_{wd}/F as a function of d/h for different values of H/h and for $\alpha = 1/4$ is graphed, for a two-level, double-bond pull test.

values of one or more of these variables have been altered. The magnitude of ΔF will depend on which side of the pulling probe rupture occurs. To distinguish between cases where rupture occurs on the terminal and where it occurs on the die side of the pulling probe the symbols $\Delta F(t)$ and $\Delta F(d)$, respectively, are used.

The following expressions for $\Delta F(t)$ and $\Delta F(d)$ in terms of h, H, α, were derived from equations (5.3.4) and (5.3.5):

$\Delta F(t)$

$$\Delta F(t) = \frac{1 + \dfrac{\alpha_1 H_1}{h_1}}{1 + \dfrac{\alpha H}{h}} \times \frac{(1-\alpha)\cos\phi + \dfrac{h+H}{d}\sin\phi}{(1-\alpha_1)\cos\phi_1 + \dfrac{h_1+H_1}{d_1}\sin\phi_1} \times \frac{\sqrt{1 + \left(\dfrac{\alpha d}{h}\right)^2}}{\sqrt{1 + \left(\dfrac{\alpha_1 d_1}{h_1}\right)^2}} - 1 \quad \text{and} \tag{5.3.10}$$

$\Delta F(d)$

$$\Delta F(d) = \frac{1 + \dfrac{\alpha_1 H_1}{h_1}}{1 + \dfrac{\alpha H}{h}} \times \frac{1 + \dfrac{H}{h}}{1 + \dfrac{H_1}{h_1}} \times \frac{\alpha\cos\phi - \dfrac{h}{d}\sin\phi}{\alpha_1\cos\phi_1 - \dfrac{h_1}{d_1}\sin\phi_1} \times \frac{\sqrt{1 + \dfrac{(1-\alpha)^2 d^2}{(h+H)^2}}}{\sqrt{1 + \dfrac{(1-\alpha_1)^2 d_1^2}{(h_1+H_1)^2}}} - 1, \tag{5.3.11}$$

where the subscript, 1, denotes the altered magnitude of the variable and no subscript denotes the initial value.

dependence of h on α

Implicit in the above expressions is the dependence of h on α for a given wire bond. To assist in visualizing how h will vary with α, it is useful to consider that the part of the wire in contact with the probe lies on an ellipse whose foci are located at the bonds.

figures 17-22

The curves shown in figures 17 thru 22 display the sensitivity of ΔT to changes in the parameters α, h, d, H, and ϕ. In each case only the quantity in question was varied.

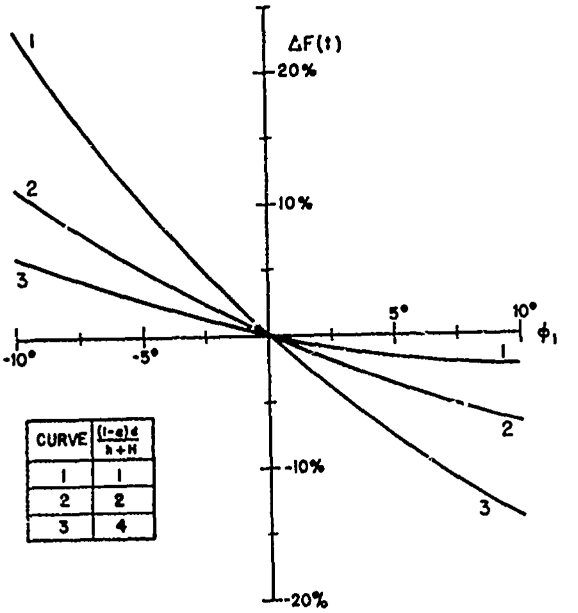


Figure 17. Dependence of $\Delta F(t)$ on pulling angle, ϕ_1, for different values of $(1 - \alpha)d/(h + H)$ and for $\phi = 0$. The dependence of $\Delta F(d)$ may be obtained by reflecting curves about the vertical axis and changing the running parameter to $\alpha d/h$.

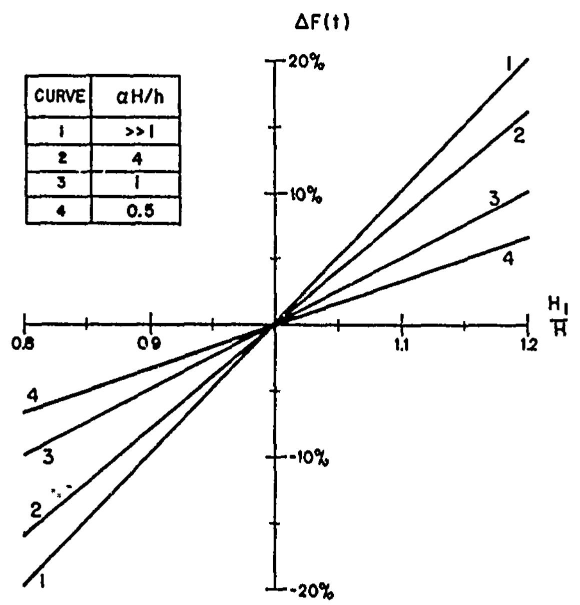


Figure 18. Dependence of $\Delta F(t)$ on the ratio H_1/H for different values of $\alpha H/h$ and for $\phi = 0$. The variation of $\Delta F(d)$ is more complex but it will be about equal to or less than that shown for $\Delta F(t)$.

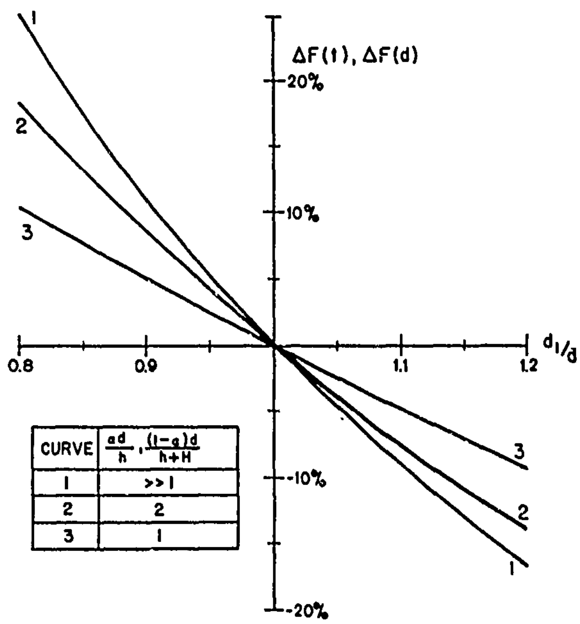
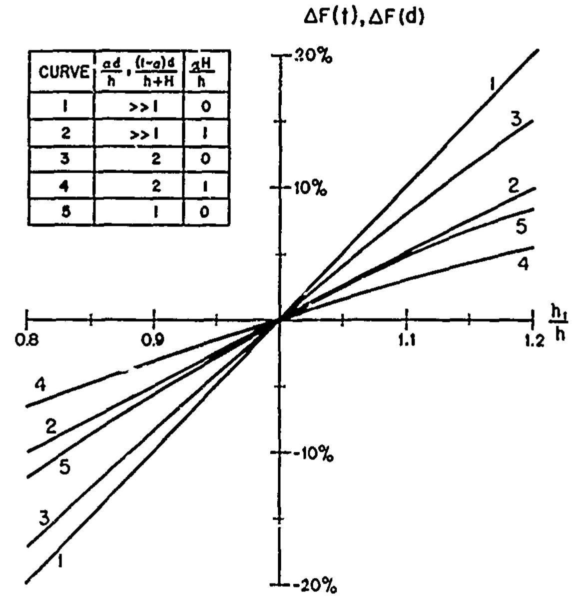
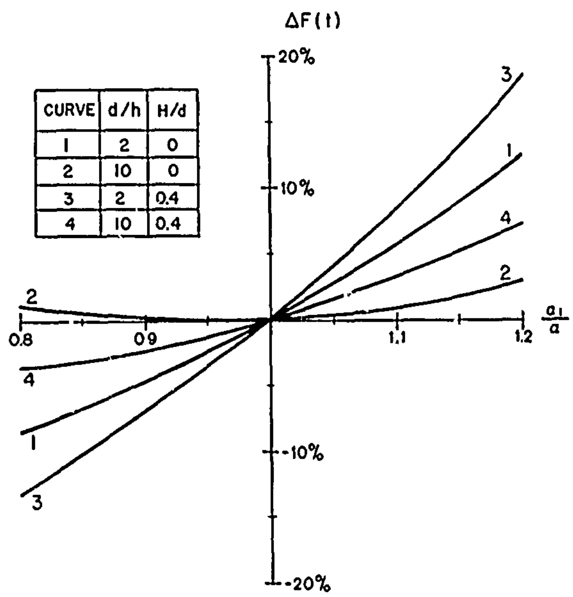


Figure 19. Dependence of $\Delta F(t)$ and $\Delta F(d)$ on d_1/d for $\phi = 0$. The running parameter for $\Delta F(t)$ and $\Delta F(d)$ are $\alpha d/h$ and $(1 - \alpha)d/(h + H)$, respectively.

Figure 20. Dependence of $\Delta F(t)$ and $\Delta F(d)$ on h_1/h for $\phi = 0$. The running parameters for $\Delta F(t)$ are $\alpha H/h$ and $\alpha d/h$; for $\Delta F(d)$ they are $\alpha H/h$ and $(1 - \alpha)d/(h + H)$.





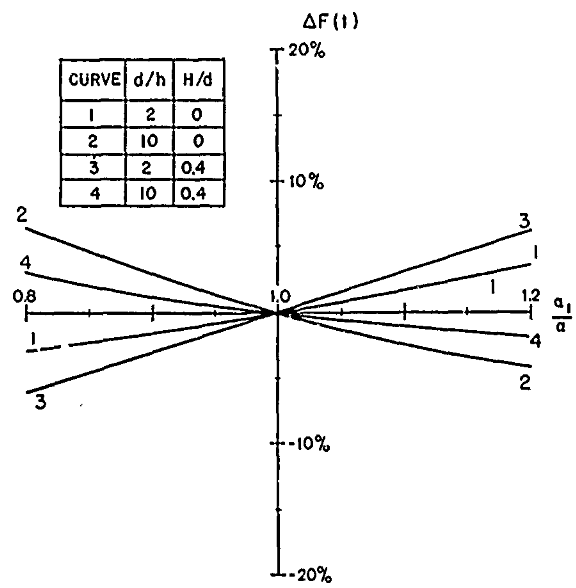


Figure 21. Dependence of $\Delta F(t)$ on α_1/α for $\alpha = 0.5$, $\phi = 0$, and different values of d/h and H/d. The dependence of h on α is included. The dependence of $\Delta F(d)$ will be similar, particularly as the squares of $(1 - \alpha)d/(h + H)$ and $\alpha d/h$ become large with respect to unity.

Figure 22. Dependence of $\Delta F(t)$ on α_1/α for $\alpha = 0.25$, $\phi = 0$, and different values of d/h and H/d. The dependence of h on α is included. The dependence of $\Delta F(d)$ will be similar, particularly as the squares of $(1 - \alpha)d/(h + H)$ and $\alpha d/h$ become large with respect to unity.

5.3.3. Discussion

discussion

wide use

The pull test is perhaps the most widely used test for wire bonds. The test is fast, easy to perform, requires little equipment, and it provides a number, the pull strength. The ease with which this number can be obtained may be a reason for the lack of attention that is often given to details of the test that may have a significant effect on the result.

incomplete specification

Despite its long use and its importance in rating the quality of wire bonds, no satisfactory standard pull test method is available. When the use of a pull test is indicated, the test conditions are under-specified. When the results of a pull test are reported, not only are the test conditions incompletely specified but so also are the pertinent physical parameters of the wire bond. Thus, in the typical situation some average pull strength is quoted and histograms may be shown, but because of the lack of other information the data are of limited usefulness and may even be misleading. When such data are used to qualify parts or to compare different wire bonds, considerable confusion and misrepresentation can occur and the technically more sophisticated competitor, as well as the user, may be penalized.

specification needs

To maximize the usefulness of pull test data especially when used to evaluate and compare wire bonds it is important to specify fully the wire bonds tested and the test conditions as well as the failure mode. The following several paragraphs discuss many of the items that need to be specified for the wire bond and the pull-test conditions.

tensile strength

To adequately identify the wire bond tested, such information as the wire material, its mechanical characteristics and cross-sectional dimensions, the bond type, the metal film(s) and the substrates at both bonding sites are needed because all may affect the pull strength measured. A particularly important wire characteristic that has a direct effect on the pull strength is the tensile strength. More useful is the tensile strength of the wire at the time of the test. Exposure of the wire to elevated temperature anneals the wire and reduces its tensile strength significantly. For example, Pankratz and Collins [70P1] reported that the tensile strength of aluminum wire with 1 percent silicon added was reduced to about 60 percent and to about 40 percent of its initial value after an exposure of one hour to elevated temperatures of 200°C and 250°C, respectively. Fully annealed wire can have a tensile strength of as little as 20 percent of its initial value.

wire span

It is necessary to have information about the average shape of the wire span.* Changes in the shape can significantly affect the pull strength measured. To indicate the magnitude of the dependence of the pull strength on the shape of the wire span in a double bond-pull test, consider two wire

*In cases where the elongation of the wire is large, such as in annealed wire, it is necessary to take this into account when providing information about the shape of the wire span.

bonds for which the same tensile force in the wire is required to produce rupture (so that if a single-bond pull test were performed both would indicate the same pull strength). Let the contact angles that the wire makes with each bonding surface be 10 degrees for one wire bond and 30 degrees for the other. The pull strength measured for the one with contact angles of 30 degrees will be about three times as large as for the other (see figure 14).*

bond efficiency

In order to evaluate and compare the pull strengths of different wire bonds, some means of normalizing the data is needed. In such an attempt, Riben *et al.* [67R1] used the term bond efficiency or the ratio of the tensile force in the wire at rupture to the tensile strength of the wire.† Riben *et al.* reported bond efficiencies of from 0.32 to 0.63 while more recently Cox *et al.* [70C1] reported bond efficiencies of from 0.8 to 0.9, all for aluminum wire ultrasonic bonds. These data were for single-bond tests where the pull strength is equal to the tensile force in the wire at rupture. For a double-bond pull test, information about the geometry of the wire bond and the location and direction of pull is needed to relate the pull strength measured to the tensile force in the wire.§ This kind of information is rarely if ever provided (or even recorded) with the consequent inability to compare different wire bonds reported in the literature in terms of their pull strengths.

span variance

The ranges of the geometrical parameters used to describe the shape of the wire span are also important. Such information can be used to estimate the contribution that variations in shape may have had on the width of the pull strength distribution. (This may be done with the help of figures 17-22).

gauge accuracy

Virtually the only specification that is given for the pull test apparatus, as may be seen in table 5, is in regard to the accuracy of the gram-force gauge reading [68D2], [71N2]. But, the requirement for accuracy in the gram-force gauge is virtually meaningless considering the incompleteness of the specification of the wire bond. For example, MIL-STD-883 requires that the accuracy be +0, -0.5 grams-force in the range of 0 to 10 grams-force. Assuming the same tensile force along the wire is required to produce rupture, variations considerably larger than 0.5 grams-force are to be expected for the different wire bond geometries that may be used in

*For wire bonds made on the same plane, 10 degrees and 30 degrees correspond to values for the ratio of loop height to bond separation (h/d) of about 0.1 and 0.3, respectively.

†Joshi [71J2] used the term bond quality factor which he defined as the tensile force in the bonded wire at rupture, when the wire is pulled parallel and close to the bonding surface, divided by the initial wire tensile strength.

§The effect on the measured pull strength of geometrical factors such as the wire span, loop height, relative height difference of the two bonds, and the location of the pulling probe on the wire span has been presented in detail in the preceeding section.

microelectronic devices. Another possible source of error will be present if the gauge, which typically uses a lever arm to transmit the pulling force, is not rotated during the test to maintain the pulling force perpendicular to the lever arm.

rate of pull

There has been some concern that the speed of the test could affect the magnitude of the pull strength measured. Riben *et al.* [66R1] mentioned observing a decrease in single-bond pull strength (magnitude not given) by increasing the speed from 0.2 in/min to 0.5 in/min ($\sim$ 5.1 to $\sim$ 12.7 mm/min). However, Leedy and Main [71B4] reported no dependence of pull strength or pull rates in the range of 1 to 77 gf/s for wire bonds with 1-mil diameter aluminum wire bonded ultrasonically to an aluminum film on silicon. The range of loading rate reported by Leedy and Main is roughly equivalent to a pulling rate range of 0.39 to 30 mm/min which includes the range of pulling rates in which Riben *et al.* reported a dependence. The higher rate of 30 mm/min may be comparable with the speed of some pull test machines used in the industry where the pull may be likened to a jerk. It should be added that the wire bonds used by Leedy and Main were constructed so that rupture occurred in the heel of the bond. The independence of the pull strength on pull speed in the range reported may not hold for wire bonds where the failure mode is rupture or peel at the bond interface or where the two bonds are on different levels [71B4].

pull rate specification

To better define measurement conditions in the pull test in any future experiments and to quantify test specification with regard to pull rate, the alternate ways of defining pull rate recommended in the ASTM standard method for tension testing [70A6] should be considered. Five ways are listed: (1) rate of straining, (2) rate of stressing, (3) elapsed time for completing part or all of the test, (4) speed of the moving head during the test, and (5) speed of the moving head when not under load. All but the last measure would be useful as a means of quantifying the pull rate. Sufficient information should be provided so that given one way it would be possible to determine the rate by another. Relations are provided in Appendix B which related the first four of the above measures for the pull rate.

probe design

Some elements in the design of the pulling probe, should be mentioned. The shape and diameter of the probe at the pulling end are important with regard to possible damage to the wire. The stiffness and the suspension of the probe are important to the control of the direction of the pulling force and the control of the location of the probe on the wire.

out of plane pull

The effect on the pull strength of variations in the pulling angle in the vertical plane containing the two bonds is indicated in figure 17. If the direction of pull is outside this plane such a twisting stress

should have a degrading effect on the measured pull strength. Leedy and Main* in preliminary attempts to measure such degradation for single-level, aluminum ultrasonic wire bonds found only small if any degradation in pull strength for angles as large as 20 degrees out of the plane of the wire loop.

probe location

The ability to locate precisely the pulling probe on the wire span is also important. The orientation of the wire may make it difficult to position the hook at the desired location and then pull the wire perpendicularly to the bonding surfaces without having the hook slide along the wire. This can occur when the bonding surfaces are at different levels. It may be possible to circumvent this difficulty by pulling in a direction which is perpendicular to the plane of the two bonds, but it may be inconvenient to manipulate the device so that the proper angle of pull is obtained. Slipping of the hook may also occur when testing ultrasonic wire bonds which have a slight bend in the wire span as a result of the fabrication procedure (see figure 7). The location of this bend may not correspond to the point where it is desired to position the probe. The procedure of deforming the loop initially in an attempt to create a bend at the desired location to prevent the probe from slipping is tedious and not always successful. Furthermore, this involves additional flexing of the wire.

nondestructive test

Thus far the comments made in this part have been related to destructive pull tests. Many of the comments, however, also apply to the nondestructive pull test which has been mentioned as a 100 percent screen test by Slemmons [69S1] and Ang *et al.* [69A1]. To substantiate the claim that the test is non-degrading to those that pass, the authors show that after a group of wire bonds has been so tested and then pulled to destruction, the bond strength frequency distribution is merely truncated at the preselected stress level.

evaluation

Polcari and Bowe [71P3] have reported the results of some preliminary evaluations of a nondestructive pull test. The test vehicles were 1-mil diameter aluminum, ultrasonic wire bonds in uncapped 14-lead integrated circuit devices made by one manufacturer. They found that prestressing once to 2 gf produced no significant statistical differences in the mean and in the standard deviation of the pull strengths of wire bonds stored for 250 hours at temperatures of 150, 200, and 250°C. However, multiple prestressing to 2 gf did appear to be degrading to wire bonds. They concluded by emphasizing that while the nondestructive test could be a valuable reliability tool it must be recognized that the proper use and adjustment of the tester would be of critical importance. Furthermore, if the nondestructive pull test were to be implemented, they would recommend that control over the variation in

*K. O. Leedy and C. A. Main, National Bureau of Standards, Washington, D. C. 20234, to be published.

loop heights be exercised by the manufacturer to minimi : variations in the stress imposed by the test.

Although there seems to be considerable interest in a nondestructive test there is also skepticism that the test is actually non-degrading. The idea of using devices whose wire spans have been pulled and, in the process, altered in shape is new and disturbing to many. Yet, there does not seem to be any reluctance about using devices after having been stressed in a centrifuge test. Another matter about which uncertainty exists is the level of stress required to cull out the weak wire bonds without degrading the remaining ones. reservations

Another reservation raised about the nondestructive pull test is the time required to make the test. In general the test will take approximately the same amount of time that it takes to make a wire bond. If in fact the nondestructive test can be used effectively, the extra testing time would be very well spent, especially for high reliability products.

5.4. Shear Test

shear test

5.4.1. Description

The shear test involves the use of a probe to apply a horizontal force to the wire bond. The shearing force necessary to rupture the bond is taken as a measure of the quality of bond adherence. This test was developed primarily to measure bond adhesion of gold ball bonds to metallization films. Other types of bonds do not generally offer a large enough area to probe. adherence test probe

The probe described in the literature [67A1], [67G1] is a pin with a blunt end. The use of a hypodermic needle tip, ground flat at the end, has also been observed during a laboratory visit. The exposed capillary at the tip accommodates the ball bond in a way which deforms it less than a pin-type probe and thereby a more uniform loading is applied to the bond. MIL-STD-883 [68D2] specifies only that the probe be of such shape that it causes a minimum of cutting at the probe edge when applied to the bond. shear strengths

Shear strengths as large as 100 grams-force have been reported [67G1]. Typical ranges reported extend from about 10 to 70 grams-force [67A1], [67G1], [69L1].

discussion

5.4.2. Discussion

Judging from the literature and personal contacts, the shear test is not widely used. There appear to be several problems with the method. One is the fundamental difficulty of designing a probe small enough to contact the deformed wire above the bond and yet strong enough to apply sufficient shearing force. Another is the operator dependence of the test resulting in part from the difficulty of contacting the bonded wire reproducibility. little used problems

During one laboratory visit it was reported that a variation of from 20 to 40 grams-force could be expected in the shearing force when different operators measured equivalent wire bonds.

metallization test

Nevertheless the method has been used to monitor and optimize the adhesion between the bond, metallization layer(s) and the substrate as well as determine the effect of various stresses on this adhesion [67A1]. Gill and Workman [67G1] found the shear test to be the only effective method for predicting poor adherence between films of gold and molybdenum. In particular they found that adherence problems are indicated by abnormally low shear strengths or when the gold film is sheared off with the wire to expose the molybdenum film.

air blast test

5.5. Air Blast Test

5.5.1. Description

An air jet from a nozzle whose diameter is much larger than the wire bond tested is directed at the device in a way which will apply a generally lateral thrust to the wire loop. The force of the air jet is adjusted so that poorly adhering bonds or wire badly deformed at the heel will be ruptured without degrading wire bonds of satisfactory strength.

use

The test is most suitable for use when the wire bonds are arranged symmetrically on the device. Either the device is rotated under the jet of air, directed at some angle from the vertical, or the device is fixed and the nozzle is moved about the device. Electrical tests follow to detect those wire bonds which have been ruptured.

Design information has generally been considered to be proprietary. No reports or published papers have been found which describe the apparatus or the method.

5.5.2. Discussion

reservations

No evidence, pro or con, is available to evaluate the effectiveness of the method. An often expressed reservation about the method is the difficulty of quantifying the stress imposed on the wire bond. Variables that affect this stress are the orientation of the wire bonds and the semiconductor die, and the design of the package. The force exerted by the air jet in turn is affected by such characteristics as the nozzle design, air pressure, angle of incidence, and the distance between the nozzle and the wire bonds. These effects have not been studied. In the face of the consequent uncertainties, the tendency is to minimize the stress level of the test and thereby reduce its potential effectiveness. Plough *et al.* [69P1] found that while the method would detect very weak wire bonds, the air jet could also cause metal-fatiguing oscillations in satisfactory wire bonds.

5.6. Push Test

push test

5.6.1. Description

new method

The new and potentially nondegrading method, a push test, has been suggested by Floyd.* The test involves the application of a force to the apex of the wire span in a direction perpendicular to the wire and parallel with the bonding surfaces. Initial, exploratory use of the method has been on ultrasonic wire bonds. An appropriately selected force is applied by a wire probe. The magnitude of the force is indicated by the deflection of the probe.† The criterion for rejecting the wire bond is either a large displacement of the wire loop at its apex (indicating plastic flow of an excessively deformed wire adjacent the bond), rupture of the wire at the heel (indicating gross deformation there), or rupture of the bond (indicating poor adherence).

rejection criterion

5.6.2. Discussion

The push test is similar to the air blast test in that a lateral force to the wire loop is used to cull out weak wire bonds. The push test offers greater control over the applied stress and greater flexibility in that it can be used conveniently even when the wire bonds are not symmetrically arranged. The testing rate can be comparable with that of the nondestructive pull test, but the test has the potential advantage of not altering the shape of the wire span and so allowing less chance for degradation. On the other hand there is then no evidence that the wire bonds have been tested. Considering the potential advantages of the method further exploration is warranted.

air blast vs. push

A basic problem is that the displacement of the wire due to the application of the force at near mid-span may not be a sufficiently sensitive measure of the condition of the heel of the bond which is usually the weakest part of the wire bond. Except for very weak wire bonds the deflection should occur mainly in the wire between the heel and the point of application, because of its much greater length. It remains to be seen if the push test can be made to be sufficiently sensitive.

problems

There are other problems which must be recognized. In its present form, the applied force is controlled by deflecting a wire probe a specified amount. Both this deflection and the maximum deflection of the wire span, of the order of a wire diameter or less, must be estimated by the operator during the test.

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*H. L. Floyd, Jr., Sandia Corp., Albuquerque, N. M., private communication. He related that the idea initially came from an unidentified engineer who used a whisker from his beard as a probe and called it the "whisker test".

†Forces as large as tenths of grams-force have been used. H. L. Floyd, Jr., private communication.

This may be a significant source for variability in the use of the method. The dependence of the stress to the wire bond on the shape and length of the wire span is present in this as in many other tests in use. Thus the maximum allowed deflection of the wire span may have to be adjusted to take the geometry of the wire bond into consideration.

ultrasonic stress test

5.7. Ultrasonic Stress Test

Knollman *et al.* [69K4] have described tests on capped devices using equipment in which a controlled level of focused ultrasonic energy is directed at the under-side of the device package. Two modes of stress were used: a pulsed mode and a cw mode with power density of up to 500 W/cm^2 for a duration of 20 to 200 μs, and up to 32 W/cm^2 for 1 to 10 s, respectively. The most prominent failure for the pulsed mode was rupture at the bond interface while for the cw mode it was rupture at the wire adjacent to the bonds.

focused US energy

needs evaluation

Not enough work has been done to evaluate the possibilities of this test method. So far the exploration of the method has been entirely empirical. A more theoretical approach is needed to provide a better understanding of the nature of the stress on the wire bond and to determine how it is affected by such things as configuration of the wire bond and the design of the package.

cleaning bath

A much less desirable method of stressing wire bonds ultrasonically is to place the uncapped device in a commercially available ultrasonic cleaning bath. An immediate problem with this method is the large variation of ultrasonic power density with location in the bath.

centrifuge test

5.8. Centrifuge Test

5.8.1. Description

purpose

The centrifuge test subjects a device to a constant acceleration in order to determine the ability of a device component to sustain the centrifugal force imposed. When the intent is to test wire bonds, the device is oriented so that the centrifugal stress either (1) ruptures poorly adhering bonds or (2) displaces wires which have an excessive loop or which are improperly placed so that they will make electrical contact with adjacent parts of the device. This rupture or displacement is detected by electrical tests following the centrifuge test.

conditions specified

The pertinent conditions specified for the test are the maximum acceleration (expressed in gravity units, g), the duration of the test at maximum acceleration, the orientation of the device with respect to the direction of the centrifugal force, any prior stresses, and the measurements to be made after the test to detect failure. The typical range of centrifugal accelerations used to test 1-mil diameter gold wire bonds is from 30,000 to 50,000 g's. A typical duration at the maximum stress level is 1 min in any one orientation.

The orientations chosen are those in which the centrifugal force is directed either away from, toward, or parallel with the bonded surfaces. The test is often preceded by other tests intended to weaken unreliable wire bonds and thereby promote their failure in the centrifuge test. Test conditions given in standard methods or reported in the literature are listed in table 6.

Table 6 - Conditions Used or Recommended in Centrifuge Test Methods

Source	Acceleration (1,000 g's)	Directions of Centrifugal Force*	Duration of Maximum Stress (min)
70D3†	not specified	six	1§
69B2	20, 40, 60, 80, 100	Y_1	1
69O1	30	—	—
69S4	10-100	Y_1 or six×	—
68B1	10-30; ≤ 200	—	—
68D2+	20¶	six or less	1
68I1#	5, 10, 20, 50, 100α	six or less	≥ 1/6
68R2	20	six	—
67G1	20, 100	X_1, X_2, Z_1, Z_2, Y_1	—
66G1	30	Y_1, Y_2, Z_1, Z_2	—
66L4	20	Y_1, Y_2	1§
66P1	20	Y_1, Y_2	—
65C5	20-40	—	—
65R1	20	six	—
65S2	40, 70, 100	—	—
64U1	10, 20	Y_1Y_2, X-Z plane	—

*Along X, Y, Z coordinate axes of device as specified in MIL-STD-883, for example; Y axis is meant to be normal to the bonding surface, subscript 1 indicates direction away from surface, subscript 2 indicates opposite direction. If all six directions are given, the word "six" is entered.

†MIL-STD-750B.

§Duration between zero and maximum acceleration must be at least 20 seconds.

×All six directions for reliability testing; Y_1 direction for screen test.

+MIL-STD-883.

¶Shall apply unless otherwise specified. Other values listed are 500; 1,000; 1,500; 3,000; 5,000; 7,500; 10,000; 12,500 g's.

#IEC Recommended Method.

αLower acceleration conditions included.

5.8.2. Analysis

tensile force calculation

The calculated tensile stress on the wire bond resulting from a centrifugal force directed away from the bonded surfaces is provided in this section. These calculations allow a better evaluation of the usefulness of a centrifuge test in testing wire bonds of a particular design than the calculations reported by O'Conner [6901, figure 3] which were for a simpler geometry and are applicable only for small values of the ratio of wire loop height to bond separation, h/d.

catenary span

It is assumed that the centrifugal force is sufficiently large so that the wire span takes the shape of a catenary. The parameters of the system are illustrated in figure 13 (section 5.3.3).

tensile force at contacts

It may be shown that the tensile forces in the wire, F_{wt} and F_{wd}, at the contact points to the terminal and die respectively are in grams-force:

$$F_{wt} = \rho\, \pi r^2\, G\, (a + h) \tag{5.8.1}$$

$$F_{wd} = \rho\, \pi r^2\, G\, (a + h + H) \tag{5.8.2}$$

where $a \approx \dfrac{d^2}{4h\,(1 + \sqrt{1 + (H/h)}) + 2H}$ for $d \gtrsim 2\,(H + h)$,

and where ρ = density of the wire (g/cm^3),

r = radius of the wire (cm),

h = vertical distance between the terminal contact surface and the peak of the wire loop (cm),

H = vertical distance between the terminal and die contact surfaces (cm),

d = horizontal distance between bonds (cm), and

G = centrifugal acceleration (in units of gravity).

approximations

Using the approximate value for a will introduce an error of less than 10 percent in F_{wt} and F_{wd} even for $d/(h + H)$ as small as 2, which is an unusual case. An exact value for a can be obtained from the relation $h + H + a = a \cosh (D/2a)$, where $D/2$ is the lateral distance between the bond at the die and the apex of the wire loop. Actually, the greatest uncertainty may result from the estimate of h, which is the distance between the apex of the wire loop and the terminal contact surface *after* the centrifugal forces have deformed the loop to describe the catenary curve.

figure 23

A useful graphical representation of equation (5.8.1) (using exact values for a) is shown in figure 23. Here, the tensile force in the wire adjacent to the bonds of a single-level, 1-mil diameter, gold wire bond subjected to a centrifugal force of 30,000 g's is shown as a function of d for

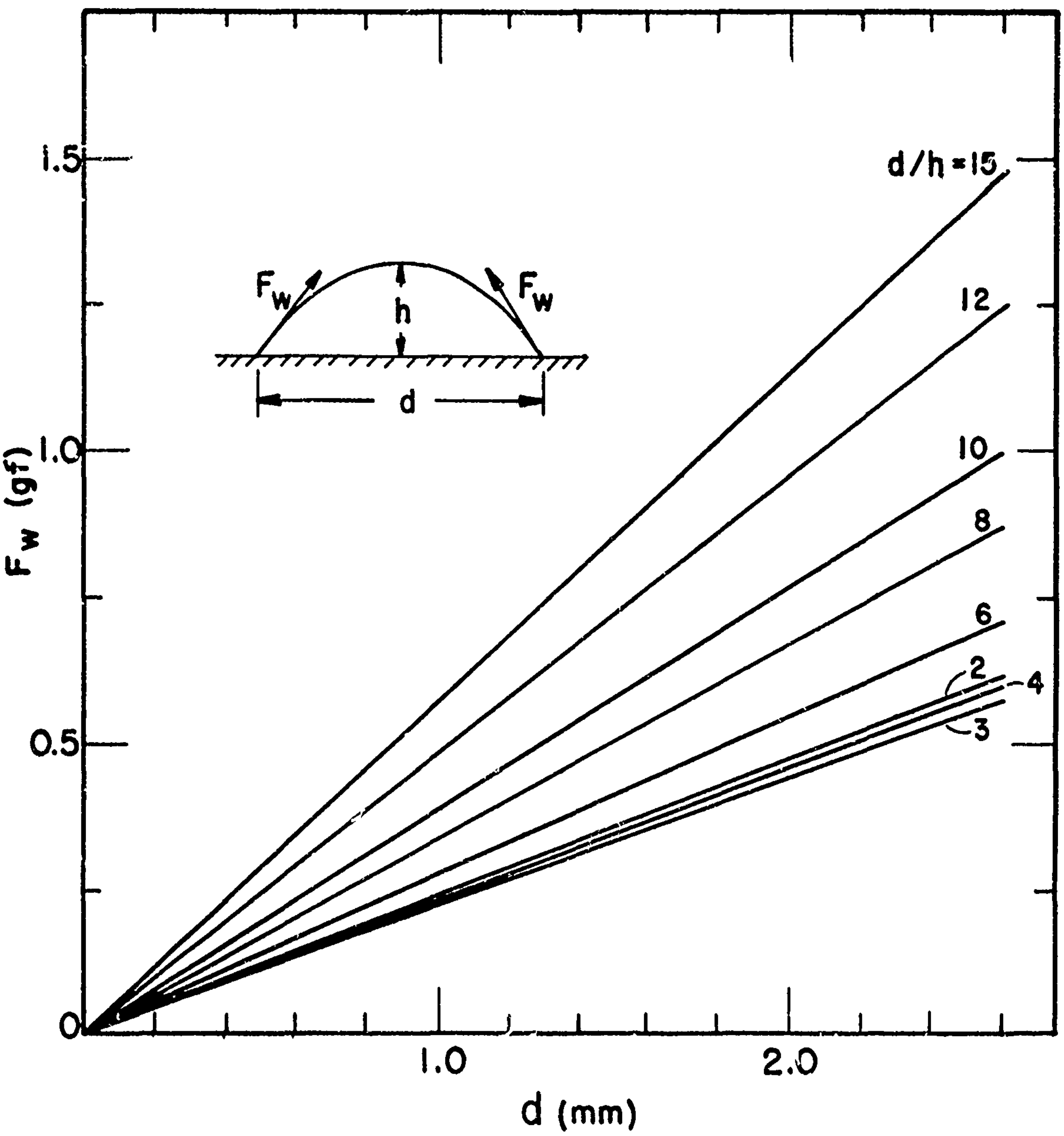

Figure 23. Tensile force, F_W, in the wire adjacent to the bonds in a single-level, 1-mil diameter, gold wire bond due to a centrifugal force of 30,000 g's directed perpendicularly away from the bonding surface is graphed as a function of d for different values of d/h. F_W for a given value of d is a minimum when d/h $\sim$ 3. Values for F_W for accelerations other than 30,000 g's may be obtained by multiplying the value for F_W by the ratio of the acceleration of interest to 30,000 g's. Values for F_W for 1-mil diameter aluminum wire bonds may be obtained by multiplying F_W by 0.14.

example

different values of d/h. The figure shows, for example, that for a wire bond with a bond separation of 0.15 cm ($\sim$ 60 mils) and a loop height of 0.015 cm ($\sim$ 6.0 mils) the tensile force in the gold wire will be about 0.55 gf. Such a tensile stress could be produced in a pull test if the hook, placed at mid-span, were pulled with a force of 0.25 gf.

explanation of F_w variation

The way in which the tensile stress on the wire depends on the variables of the wire bond may be seen by first considering the single level case where H = 0 and where d $\geq$ 2h so that the approximate value for α may be used. The tensile forces at the wire ends are equal and given by

$$F_w \gtrsim \rho \pi r^2 G \left(\frac{d^2}{8h} + h\right) . \qquad (5.8.3)$$

For a constant acceleration, F_w decreases as h is increased from a value small in comparison with d. This follows because the angle that the wire makes with the horizontal, θ, increases and thereby decreases the component of the centrifugal force along the wire. When h becomes comparable with d, F_w increases with h. This follows because the increase in wire length for a unit increase in h is larger and the consequent increase in mass and hence centrifugal force will dominate. The dependence of the tension in the wire at the bonds as H is increased from zero follows in a similar way from the way changes in d, h, and H affect the angles θ_t and θ_d and the length of the wire.

5.8.3. Discussion

widely used

The centrifuge test is widely used in the industry. It is regarded by many as a reliable, nondestructive method of screening for defective gold wire bonds, especially when preceded by other stress tests such as temperature cycling, mechanical shock, or vibration tests. O'Conner [6901] has indicated that while stress levels due to accelerations of from 40,000 g's to 60,000 g's are more effective, a 30,000 g's acceleration level is specified in MIL-STD-883 because such equipment is generally available and the test at this level can be performed without special jigging. If accelerations much greater than 50,000 g's are used, there is a risk of damaging other components of the device.

stress levels

It is generally agreed that the test is not useful for screening aluminum wire bonds because of the much lower density of aluminum. However, there are those in the industry who believe that even for gold wire the centrifuge test is acceptable for weeding out only grossly defective wire bonds [67A1]. Basic to their objections is that the test does not impose a significant stress unless excessively large accelerations are used.

limitations

5.9. Mechanical Shock Test

mechanical shock test

5.9.1. Description

The purpose of the mechanical shock method is to evaluate the structural integrity of components and to determine their suitability for use where they may be subjected to non-repetitive mechanical shocks such as in handling or in operation. purpose

In a typical test the device is first accelerated either by free-fall or by pneumatic means and then brought to a sudden halt on striking an impact pad. The test conditions that may be specified are the maximum deceleration (in gravity units); the duration of the impact or shock pulse-width; the direction of the stress (usually along one or more of the principal axes of the device package); and the number of shocks per direction. MIL-STD-750B [70D3] is one of the rare domestic tests which specifies the shape of the shock pulse. The IEC [67I1] specifies the use of one of three basic pulse shapes: saw-tooth, half-sine, and trapezoidal. test conditions

Test conditions of standard methods and methods used and reported in the literature are listed in table 7.

5.9.2. Discussion

As will be discussed later, the stress imposed by a mechanical shock test is less than twice the stress imposed by a centrifuge test at a constant acceleration equal to the peak shock-induced deceleration and directed in the same direction, neglecting the uncertain effect of the number of vibrations that are generated. Because the largest peak acceleration listed in table 7 is 6,000 g's and considering the small stress that a centrifuge test at twice that acceleration would impose, the mechanical shock test will not stress most wire bonds greatly. stress level low stress

To make the test more severe by increasing the amplitude of the shock can result in deformation of the package at impact unless special supporting structures are used. The fact that some package designs do not readily allow means for support along one or more axes increases the inconvenience of the method. Shurtleff [69S4], however, expressed satisfaction with the method for culling out weak bonds. He suggested that electrical monitoring during the shock would improve the effectiveness of the test but the increased difficulty and expense incurred would normally preclude the use of any monitoring. stress limitation

Lombardi *et al.* [66L4] suggested that the shock test represents a compromise between the centrifuge and variable-frequency vibration tests in that it does not usually impose on the wire as large a force as the centrifuge shock vs. centrifuge & variable frequency

Table 7 - Conditions Used or Recommended in Mechanical Shock Test Methods

Source	Peak Acceleration (1,000 g's)	Shock Pulse Width (ms)	Shock Pulse Shape	Number of Shocks (each direction)	Direction of Shock
70D3[§§]	§	+	half-sine	×	×
69B2	1.0	—	—	5 to 60	Y_1†
69S4	1.5 to 6.0	—	—	5 to 10	*
68D2[××]	1.5[¶]	0.1 to 1.0	—	5	*
67I1[++]	3.0, 1.5, 1.0, 0.5,...#	0.2, 0.5, 1.0, 1.0,...∝	saw tooth, half-sine, and trapezoidal**	3	††

* Along both directions of the three major coordinate axes of the device as specified in, for example, MIL-STD-883 [68D2], for a total of six directions.

† Y axis is meant to be normal to the bonding surface; subscript 1 indicates the direction away from the surface.

§ Value to be specified, ±20 percent.

× To be specified.

\+ Value to be specified. Tolerances: for $\tau \geq 2$ ms, the greater of ±0.6 ms or ±15 percent of τ; for $\tau \leq 2$ ms, the greater of ±0.1 ms or ±30 percent of τ.

¶ Shall apply unless otherwise specified. Other values listed are 500; 3,000; 5,000; 10,000; 20,000; and 30,000 g's.

\# Other values are listed. Tolerances: for saw-tooth and half-sine shaped pulse, ±15 percent; for trapezoidal shaped pulse, ±20 percent.

∝ Other values are listed.

**Tolerance bands are provided.

††Each direction of three mutually perpendicular axes chosen to impose maximum stress (total of six directions).

§§MIL-STD-750B.

××MIL-STD-883.

++IEC Recommended Method.

test nor as wide a frequency spectrum as the variable-frequency test.* He reported further that several manufacturers believed that one would not cull out potential device failures with the shock test which the centrifuge or variable-frequency tests had not removed. Thus, the use of the mechanical shock test would be redundant if the other two tests were used. However, if testing is to be minimized at the sacrifice of screening effectiveness, the shock test could be used in their stead. The validity of these propositions is not supported by any experimental data.

*Actually for a half-sine excitation pulse with a 0.1 ms pulse width, as an example, the shock test would generate significant energy at frequencies higher than the 2 kHz maximum used in the variable-frequency test methods.

Considering the test in terms of the mechanical response of the wire bond, the use of the term shock is somewhat of a misnomer. The mechanical response time of the wire span is either comparable with or less than the shortest mechanical pulse duration used (0.1 ms). (For an estimate of the lowest resonant frequency of a wire bond see Appendix A.) In essence, the basic stresses to the system result from the amplitude and the number of vibrations induced in the wire span by the mechanical pulse. The number of the vibrations depends on the damping of the wire loop. Thus, if the wire has been annealed, through earlier exposure to high temperatures, fewer oscillations with smaller amplitudes occur and the resulting flexure stress may be less. However, irreversible changes occur in annealed wire at smaller bending and torsional stresses than unannealed wire.

"shock"

types of stress

To discuss the test in terms of the magnitude of the induced deflection and stress, it is useful to define a dynamic-to-static deflection or stress ratio, K:

deflection stress

$$K = \frac{\text{maximum wire deflection or stress by a mechanical pulse}}{\text{wire deflection or stress induced if peak acceleration of mechanical pulse were applied statically}} .$$

As a rule of thumb, the upper bound for K is 2 [48F1], [65R3, p. 768], [67I1]. How much less than 2 it is depends on the shape and duration of the pulse and on the lowest resonant frequency of the wire loop. The typical case occurs when the lowest resonant frequency of the wire loop is greater than the inverse of the duration of the excitation pulse (compare table 7 and figure A2 of Appendix A). In this case, K tends to be larger (but is bounded by 2) the lower the resonant frequency.* The test is therefore most severe for mechanical shocks in a direction normal to the plane of the wire loop, because the lowest resonant frequency in this case is that for the lateral vibration mode perpendicular to the plane of the wire span.†

Changes in the shape of the excitation pulse will produce significant differences in K. Consequently the IEC in its recommended test method has required the specification of the shape of the shock pulse. For the purpose of reproducibility, the use of a saw-tooth shaped pulse is suggested because it produces the least variation in vibration amplitude with changes in pulse duration and resonant frequency [67I1].

shock-pulse shape

*If the lowest resonant frequency is less than the inverse of the duration of the excitation pulse, as may be the case for gold wire bonds with large bond separations, K decreases to zero the lower this resonant frequency is.

†The resonant frequency for the lateral vibration mode is significantly less than those of the other two modes, except for wire loops where h/d is small. For the straight wire case (h/d = 0) the resonant frequencies for the lateral and extensional modes are equal, as may been seen in figure A1.

ripples

The IEC method [67I1] also stresses the need to minimize any ripples on the shock pulse in order to maximize the reproducibility of the method; ripple is considered to be the most significant distortion of the shock-pulse shape. It is therefore with some concern that such ripples are noted in a display of a typical impact shock pulse from a pneumatic shock tester described recently in the literature [71K1].

variable frequency vibration test

5.10. Variable Frequency Vibration Test

5.10.1. Description

purpose

The purpose of the variable frequency vibration test is to excite and rupture any device components, including wire bonds, having a resonant frequency within the range swept. The selection of the frequency range is subject to the constraints of test equipment available and an estimate of the frequency components of the kinds of shock and vibrations the device may encounter in its life. In a typical test the device is vibrated sinusoidally through a range of frequencies for one or more cycles. A minimum cycle duration is usually specified. The test is repeated along each of the three principal axes of the device. The maximum acceleration (in gravity units) is also specified, sometimes with a limitation on the maximum amplitude at the lowest vibration frequencies thus reducing the peak acceleration there. The test conditions in standard methods and methods reported in the literature are listed in table 8.

test conditions

5.10.2. Discussion

test ineffective

The variable frequency vibration test does not impose a significant stress on most wire bonds and so the test is generally ineffective. The lowest resonant frequency of most wire bonds is many times larger than the maximum vibration frequencies listed in table 8 (see Appendix A). Hence, the dynamic deflection of the wire and the induced stress will at most be only slightly larger than that induced if a constant acceleration equal to the peak acceleration were applied [65R3, pp. 368 and 370]. The maximum acceleration used is usually less than 100 g's which would produce vibrations in the wire with a negligible amplitude. Krieg and Murfin [69K2] introduced a scale factor to transform a system to a larger size where intuition can perhaps be of greater help in estimating the severity of the stress imposed. For example, using their concept of a scale factor, a 1-mil diameter aluminum wire, 0.127 cm long and subjected to 100 g's peak acceleration at a driving frequency of 2 kHz is equivalent to a 2.5-cm diameter aluminum rod, 125 cm long being driven at a frequency of 2 Hz to a peak acceleration of 0.1 g's (equivalent to a maximum displacement of about 1.2 cm), hardly a stressful condition.

Table 8 - Conditions Used or Recommended in Variable Frequency Vibration Test

Source	Peak Acceleration (g's)	Frequency Range (Hz) (logarithmic scan)	Sweep Rate	Duration or Number of Cycles in Each Direction	Direction of Vibration
70D3#	≥ 20	100-2000	≥ 4 min/cycle	4	*
69S4	2-20	20-2000	—	—	—
68D2∝	20, 50, 70§	20-2000	≥ 4 min/cycle	4	*
66I1**	1, 2, 5, 10, 15, 20, 30, 50×	10-5000 10-2000 10-500+ ¶	∿ one octave/min	1/2, 1 1/2, 6, 30, 150 hr	†
66L4	30	10-2000	4 min/cycle	—	*

* Along the three major coordinate axes of the device package as specified in, for example, MIL-STD-883.

† Three mutually perpendicular axes chosen to impose maximum stress.

§ Below about 80, 127, and 150 Hz for the respective peak accelerations, the total excursion is limited to 0.06 inches.

× Below 60 Hz the total excursions are limited to those at 60 Hz for the peak acceleration levels listed. Vibrational amplitude tolerances are given for "control" and "fixing" points.

+ More and narrower ranges are included.

¶ A linear sweep may be used if the sweep rate does not exceed one octave per minute.

MIL-STD-750B.

∝ MIL-STD-883.

**IEC Recommended Method.

Shurtleff [69S4] indicated this basic problem of low stress. MacKenzie and Carpenter [67M1] reported that while vibration tests at peak accelerations of up to 70 g's caused no failures in gold wire bonds to aluminum films, they did cause a significant number of package failures.

5.11. Vibration Fatigue Test

vibration fatigue test

5.11.1. Description

purpose

The purpose of the vibration fatigue test is to determine if the components of the device, including wire bonds, can withstand relatively long periods of low-frequency sinusoidal oscillations without metal fatigue. The test involves vibrating the device at a low, fixed frequency, for many hours, along each of the three principal axes of the device package. The maximum acceleration (in gravity units) or vibrational amplitude is specified. The test conditions in standard methods and methods reported in the literature are listed in table 9.

test conditions

Table 9 - Conditions Used or Recommended in Vibration Fatigue Tests

Source	Peak Acceleration (g's)	Frequency (Hz)	Duration Per Direction (hr)	Direction of Vibration
70D3[×]	$\geq$ 20	60 ± 20	$\geq$ 32 ± 8	*
69S4	2 - 10	60	100[†]	—
68D2[+]	20, 50, 70[§]	60 ± 20	$\geq$ 32 ± 8	*
65C5	30	60	32	—

*Along the three major coordinate axes of the device packages as specified in, for example, MIL-STD-883.

†Whether duration is for each direction or for all directions is not specified.

§Acceptable alternative to 20 g's is a constant total excursion of 0.06 inches.

×MIL-STD-750B.

+MIL-STD-883.

5.11.2. Discussion

The vibration fatigue test is an ineffective way to cull out weak wire bonds for the reasons stated under the variable frequency vibration test. Shurtleff [69S4] adds that the duration of the test and equipment maintenance during the test makes it prohibitively expensive as a 100 percent screen test.

short-duration stress pulse test

5.12. Short-Duration Stress Pulse Tests

The use of short-duration stress pulses to apply large tensile stresses to the wire bond has been explored by Floyd [68F1]. The stress pulses are generated by the absorption of pulses of high energy electrons in an absorbing plate fastened to the base of the device package. The deposition occurs in a time short compared with the time that a stress inhomogeneity will decay; thus it may be assumed to occur instantaneously and to generate a thermally induced compressive stress pulse. Because the momentum of the incident electrons is negligible, a tensile stress wave follows as the compressive stress wave propagates so as to maintain zero total momentum. Upon reaching a free surface, such as the top surface of a wire bond or a semiconductor chip, the compressive stress pulse is reflected as a tensile wave. This results in an amplified tensile condition in regions where the reflected tensile wave overlaps the incident tensile wave. In these regions the tensile stress may be high enough to exceed the spall threshold along some plane and cause device

electron deposition

spallation

failure. Sufficiently great tensile stresses have been generated with adequate resolution to cause a range of failures in a number of devices, from rupture of the wire bonds at the terminal and the semiconductor die to fracturing of the semiconductor die itself. These results were duplicated by the use of a stress-wave-analyzing computer code [68F1]. This method has been referred to elsewhere [69P1] as an electronic anvil test.

anvil test

Another method for generating short stress pulses is by the use of explosively accelerated plates, sometimes called the *plate-slap* or the *flyer-plate* method. Floyd [68F1] indicated that the momentum transfer in such techniques can cause spurious stresses which make analysis difficult.

plate-slap, flyer-plate methods

5.13. Temperature Cycling and Thermal Shock

temperature cycling and thermal shock test

5.13.1. Description

Exposing the device alternately to two temperature extremes is a commonly used method to test the ability of the wire bonds as well as other parts of the device to withstand the mechanical stresses that result from differences in the thermal coefficients of expansion of the constituent parts. The main justification for such tests is the expectation that the device will be exposed to similar temperature extremes prior to and during its operational life.

purpose

Whether the test is referred to as thermal shock or temperature cycling depends on the transfer time between the two temperature extremes. The transfer time for shock tests is of the order of seconds while for cycling tests it is usually of the order of minutes. Air chambers are usually used in temperature cycling tests while liquid baths are used in thermal shock tests. For temperature cycling tests, the minimum time spent at each temperature extreme is longer in order to allow the device under test to attain the ambient temperature.

transfer time

The extremes of temperature used usually fall within the range of −196 to +300°C. A common low-temperature extreme is about −65°C while a greater variation in the high-temperature extreme is seen: gold-wire, thermocompression bonds to aluminum films are usually tested to 125°C or 150°C, aluminum wire bonds to about 200°C, and gold-wire to gold-film bonds have been tested to 300°C. Some temperature cycling tests also include an intermediate period near room temperature. The minimum number of cycles used in a screening test is about 5 to 15. When tests are used to stress wire bonds to failure, hundreds or more cycles may be used. The test specifications of MIL-STD-883 and MIL-STD-750B for the temperature cycling and thermal shock tests are listed in table 10. The conditions of most of the other tests used and described in the literature are similar to one of these.

test conditions

Table 10 - Conditions Used or Recommended in Temperature Cycling and Thermal Shock Tests

Source	High : Temperature (°C)	Low Extremes (°C)	Maximum Transition Time	Minimum Time at Temperature Extreme	Minimum Number of Cycles
68D2§	125^{+3}_{-0}	-55^{+0}_{-5}*	5 min	10 min	10
	150^{+5}_{-0}	-65^{+0}_{-5}	5 min	10 min	10
	200^{+5}_{-0}	-65^{+0}_{-5}	5 min	10 min	10
	350^{+5}_{-0}	-65^{+0}_{-5}	5 min	10 min	10
	500^{+5}_{-0}	-65^{+0}_{-5}	5 min	10 min	10
68D2×	100^{+5}_{-0}	0^{+0}_{-5}	10 s	5 min	15
	125^{+5}_{-0}	-55^{+0}_{-5}	10 s	5 min	15
	150^{+5}_{-0}	-65^{+0}_{-5}	10 s	5 min	15
	200^{+5}_{-0}	-65^{+0}_{-5}	10 s	5 min	15
	150^{+5}_{-0}	-195^{+5}_{-5}	10 s	5 min	15
	200^{+5}_{-0}	-195^{+5}_{-5}	10 s	5 min	15
70D3+	100^{+0}_{-5}	0^{+5}_{-0}	3 s	15 s; 5 s†	5
	100^{+0}_{-5}	0^{+5}_{-0}	10 s	5 min	5

*Cycles include a period of not more than 5 minutes at an intermediate temperature of $25° {}^{+10°}_{-5°}$ C.

†At the high and low temperature extreme, respectively.

§MIL-STD-883, method 1010.

×MIL-STD-883, method 1011.

+MIL-STD-750B, method 1056.1, conditions A and B.

ordering of tests

The ordering of a series of tests is important. If temperature cycling and thermal shock tests are used as part of a series of screening tests then it is important that they be performed before mechanical stress tests (such as the centrifuge and vibration tests) are made so that the wire bonds weakened by the temperature stress tests can be culled out [66G1], [66L4], [69O1].

monitored thermal cycle

The use of a "monitored thermal cycle" test [71H2] is discussed in section 5.14.3. In this test the device is also exposed to temperature extremes. The thermal-induced stresses are used to dislodge or shift poorly adhering wire bonds which are detected by performing electrical continuity tests.

power cycling

Power cycling tests produce stresses in wire bonds similar to those induced during temperature cycling and thermal shock tests. However, the

stresses as a result of wire flexure are less in a power cycling test for the same maximum device temperature. This follows because the expansion of only part of the wire, nearest the semiconductor chip where the power is dissipated, contributes appreciably to the wire flexure.*

5.13.2. Analysis

The tensile and flexing stresses resulting from the differential thermal expansion of the wire bond and the device header will be discussed in this section. These stresses are important considerations in not only temperature cycling and thermal shock tests, but also in power cycling tests where there is sufficient time during the power-on and power-off parts of the cycle for the system to approach thermal equilibrium.

bonding and tensile stress

To estimate the order of magnitude of stress levels that may be generated in the wire adjacent to the bonds, Krieg and Murfin [69K2] made approximate calculations of the maximum bending and membrane stresses in the wire (away from the bonds) of specific wire-span configurations. These calculations did not include the wire ends because of computational difficulties. The results of these calculations showed that these stresses increase as the contact angle is decreased. Their expressions do not extrapolate to the case of a straight wire. In this case, if there is no buckling, the tensile stress is given† by $\sigma = E(\beta_w - \beta_s)(T - T_o)$, where E is the modulus of elasticity, β_w and β_s are the thermal coefficients of expansion of the wire and surface, respectively, and T_o and T are the initial and final temperatures, respectively. For a 1 mil-diameter aluminum wire where $E \approx 7 \times 10^8$ gf/cm^2 (70 GN/m^2) and $\beta_w - \beta_s = 15 \times 10^{-6}$ °C^{-1}, the tensile force will increase by about 0.05 grams-force per degree Celsius decrease in temperature.

flexing stress

An important stress, especially as the number of cycles is increased, is the flexing that the wire undergoes adjacent the bonds. The most obvious manifestation of this flexing is the change in loop height, h. Gaffney *et al.* [68G2] observed loop height changes of as much as several wire diameters in small-signal transistors during low-repetition-rate pulsed power operation. They concluded that the wire-fracture failures they found were due to flexing-induced fatigue of the wire. Recently, Ravi and Philofsky [72R1] documented

*An analysis has been made by Phillips [72B1], [72B3] of the thermal-expansion induced changes in loop height of a 500-mW, 50-mA silicon transistor in a TO-18 package which are produced by the dissipation of power in the semiconductor die as would occur in a power cycling test. His analysis has shown that the temperature gradient is linear along the wire between the die and the terminal in an unencapsulated device, indicating that the radiation and convection heat losses from the wire are negligible. Joule heating in the wire was assumed to be negligible at the relatively low current levels considered.

†For example, see P. R. Lancaster and D. Mitchell, *The Mechanics of Materials*, McGraw-Hill, New York, 1967, p. 40.

the formation and propagation of microcracks and eventual failure by fracture at the heel of ultrasonic bonds in a dynamic SEM display of wire flexing as a result of such power-on-off operation.

change in h

Gaffney *et al.* [68G2] also calculated the change in the loop height for a circular-shaped wire loop as a result of the thermal expansion of the wire, uniformly heated, for a fixed horizontal bond separation.* Their expression is rearranged below

$$h \approx h_o\sqrt{1 + \frac{2n(3n + 1)}{(3n + 5)\ (n - 1)}\,\beta_w\ (T - T_o)} \qquad (5.13.1)$$

where n is the ratio of the wire length at $T = T_o$ to the bond separation. This expression is developed from the relationship $s \approx 8\sqrt{h^2 + (d/2)^2} - d$ which relates the circular-arc length of the wire, s, to the loop height and bond separation to within 2 percent for ratios of h/d as large as 0.5. Using this relationship to obtain

$$h_o \approx \frac{\sqrt{3}}{8}\ d\sqrt{(3n + 5)\ (n - 1)}\ , \qquad (5.13.2)$$

n may be obtained in terms of h_o and d which when substituted into equation (5.13.1) provides an expression in terms of quantities that may be easily measured:

$$h \approx h_o\sqrt{1 + \frac{1}{4}\left(7 + \frac{3}{2}\frac{d^2}{h_o^2}\right)\beta_w(T - T_o)} \qquad (5.13.3)$$

For most practical cases and where d/h_o is not excessively large, the square root term may be expanded to obtain

$$h \approx h_o\left[1 + \frac{1}{8}\left(7 + \frac{3}{2}\frac{d^2}{h_o^2}\right)\beta_w(T - T_o)\right]. \qquad (5.13.4)$$

In these cases, h is directly proportional to $T - T_o$ and the percentage change in h increases as h_o decreases. Similarly, it may also be shown by differentiating equation (5.13.1) that dh/dT decreases with increasing values of $T - T_o$.

*The results of these calculations were presented at the conference but not subsequently published.

While the change in loop height offers a convenient measure of flexing, the more meaningful measure is the change in the contact angles. The remainder of this section will deal with the results of calculations made of the thermal-induced changes in contact angle of a single-level wire bond assuming the configuration of the wire space remains unchanged under expansion or contraction as a result of changes in the ambient temperature.

change in contact angle

The changes in the contact angles were calculated for two cases: where the wire span forms the two equal arms of an isosceles triangle and where it forms a circular arc. These two shapes were chosen in an attempt to bracket a range of loop shapes that might be encountered. It was found that for a circular arc shaped loop

$$\frac{\sin\psi}{\psi} = \frac{\sin\psi_o}{\psi_o}\left[1 - (\beta_w - \beta_s)(T - T_o)\right], \qquad (5.13.5)$$

and for an angular shaped loop,

$$\cos\psi = \cos\psi_o\left[1 - (\beta_w - \beta_s)(T - T_o)\right], \qquad (5.13.6)$$

where ψ, ψ_o = the final and initial contact angles, respectively,

ψ = $2\tan^{-1}(2h/d)$, for the circular arc span,

ψ = $\tan^{-1}(2h/d)$, for the angular shaped span,

h = loop height (cm),

d = bond separation (cm),

β_w, β_s = the thermal coefficient of expansion of the wire and bonding surface meterial, respectively ($°C^{-1}$), and

T, T_o = the final and initial ambient temperature, respectively (°C).

The calculations incorporated the fact that both β_w and β_s are very much smaller than unity.

Using the above equations the change in contact angle, $\psi - \psi_o$, versus h_o/d_o is graphed in figure 24 for the two wire-span shapes, for a differential expansion between the bonding wire and bonding surface, $(\beta_w - \beta_s)(T - T_o)$, equal to 0.004.* Scales are also provided in figure 24 to show the percentage change of h_o/d_o for both wire-span shapes. The thermal-induced change in contact angle and h/d increases in magnitude as the initial contact angles or as h_o/d_o decreases. For a given initial contact angle or h_o/d_o, the change in contact angle is less for the angular span

figure 24

*For a wire bond with aluminum wire ($\beta_w \approx 24 \times 10^{-6}$ °C^{-1}) and a base material with a β_s of 4×10^{-6} °C^{-1}, the value of 0.004 for $(\beta_w - \beta_s)(T - T_o)$ represents a temperature change of 200°C.

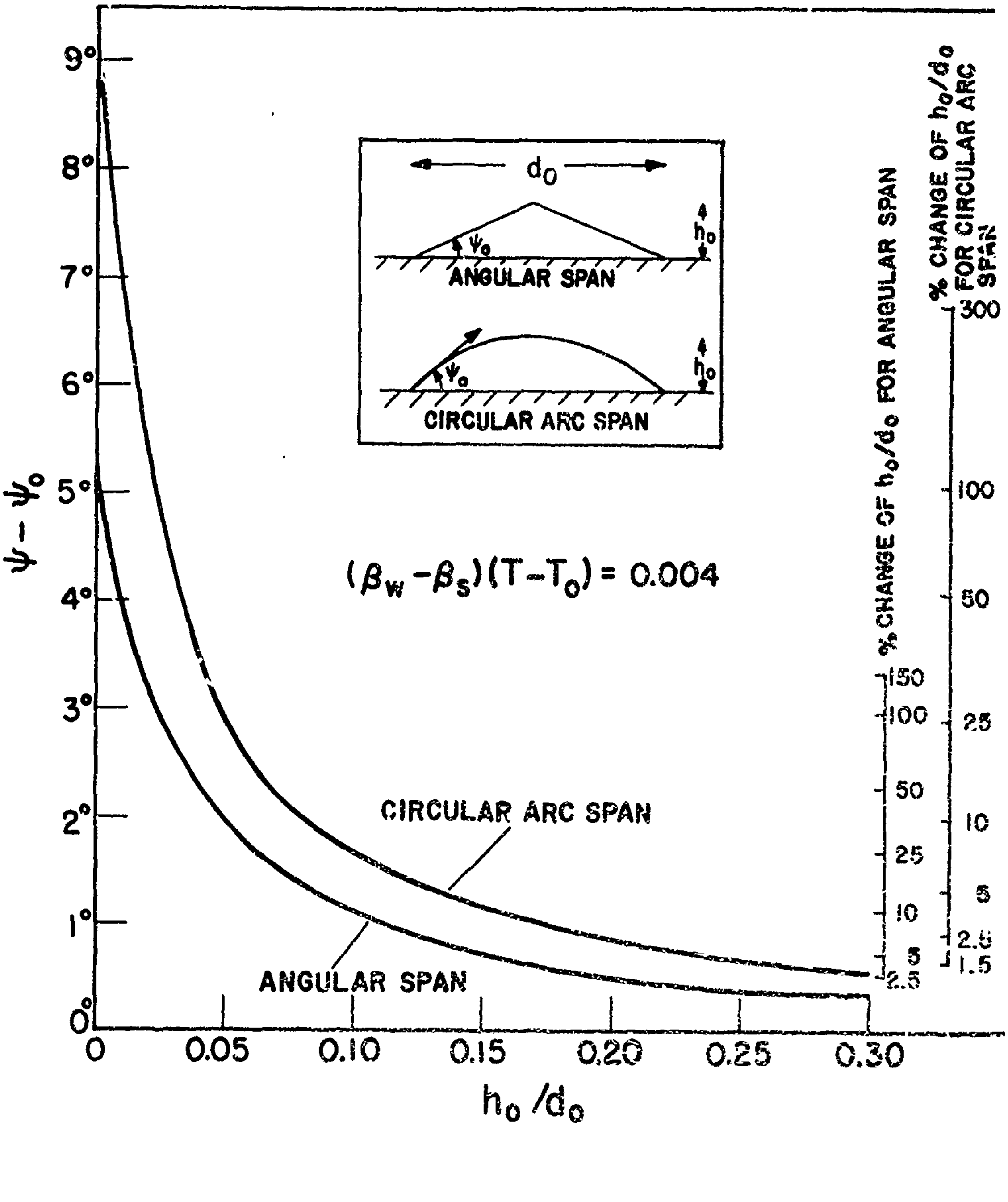

Figure 24. Change in contact angle, $\psi - \psi_o$, versus initial value of the ratio of the wire-loop height to the wire span, h_o/d_o, for a differential expansion between the wire and the bonding surface, $(\beta_W - \beta_S)$ $(T - T_o)$, of .004. Scales parallel to the $\psi - \psi_o$ axis are provided to show the percentage change in h_o/d_o for each wire-span shape.

than for the circular-arc span. The difference between the curves for the two wire-span shapes shows how sensitive is the temperature-induced change in contact angle and h/d on the shape of the wire span.

$\psi - \psi_o \propto h - h_o$

To assist in estimating the thermal-induced change in contact angle, $\psi - \psi_o$ (in degrees), from an observed change in loop height, the following expression for the circular-arc span is given for conditions when $(h_o/d_o) << 1$ and $d \cong d_o$. Then,

$$\psi - \psi_o \approx 4 \frac{180}{\pi} \frac{h_o}{d_o} \frac{h - h_o}{h_o} \cong 230 \frac{h - h_o}{d_o} \quad (5.13.7)$$

for a circular arc span. The expression for the angular arc span is the same except the numerical factor should be halved. The above expression shows that for the conditions stated, the thermal-induced change in contact angles is proportional to the thermal-induced change in loop height. Phillips [71B5] reported earlier that changes in contact angle were approximately proportional to the change in loop height for wire flexing resulting from low-repetition-rate power on-off cycling conditions.

discussion

5.13.3. Discussion

contradictory evaluation

Contradictory evaluations have been made of temperature cycling and thermal shock tests. Bell [69B1] considered these tests as effective for screening bond failures as did Hakim and Reich [65H3] who also regarded them as effective in comparing production processes or products. On the other hand, Plough *et al.* [69P1] dismissed the usefulness of thermal shock tests on ultrasonic wire bonds, saying that they did not induce failures even in wire bonds known to be weak. On one thing there is general agreement. The thermal shock test is regarded as the more severe test and is therefore sometimes used to accelerate failure of those devices which would eventually fail as a result of temperature cycling tests. However, there has been no experimental work published to document this opinion.

wire bonds not stressed equally

The reason for disagreements about the usefulness of temperature cycling and thermal shock tests is that all wire bonds are not equally stressed by these tests. As discussed in the analysis section, an important stress especially as the number of cycles is increased is the flexing that the wire undergoes adjacent to the bonds. Obviously the magnitude of the flexing is affected by the differences in the thermal coefficients of expansion of the constituent parts of the wire bond and by the shape of the wire span. The magnitude of this flexing increases for smaller values of h_o/d_o or smaller initial contact angles for a given change in temperature

dependence on h_o/d_o

(see figure 24). Phillips [72B1], [72B2] reported that a group of 95 transistors fabricated with aluminum wire bonds having loop heights of 300 to 375 μm survived more than 100,000 slow power cycles without a failure. In earlier groups where the loop heights were only about 50 to 100 μm,* failures began to occur from a few hundred to a few thousand cycles. The bond separation in all transistors was about 1.0 mm.

process dependent factors

It is important to realize that the magnitude and effect of the flexing-induced stress is also affected by such factors as the extent of work hardening in the wire, deformation of the wire adjacent to the bond, and the existence of microcracks or other defects in the heel of the bond. That such factors are important is indicated by the reports of Gaffney [68G1] where the wire failure rate as a result of wire flexing resulting from low-repetition-rate pulsed-power operation was "severely" dependent on the bonding process for aluminum wire bonds. Similarly, Villella and Nowakowski [70V1], [71N3] found the degree of deformation at the heel of the aluminum-wire bonds could markedly affect the failures due to wire flexing, resulting from such on-off power operation. Both Gaffney [69G1] and Villella and Nowakowski [70V1], [71N3] noted that devices with gold-wire thermocompression ball or wedge bonds did not exhibit this reliability problem, presumably because of the greater ductility of gold. Phillips [71B5] has pointed out an additional consideration when iron-nickel-cobalt headers are used. The differential thermal coefficient of expansion of the header material and gold wire is about half that for the case where aluminum wire is used. Thus, the thermally induced stresses in wire bonds made with gold wire would be significantly less than for wire bonds with aluminum wire, for such a header. Recent work by Bevington *et al.* [70B1] with devices where the wire bonds are embedded in plastic serves as a good example to show that the test stress depends greatly on the embedding materials used in the plastic devices. Phenolic encapsulated devices were the most resistant to degradation due to thermal shock tests. Epoxy encapsulated devices were the least resistant and silicone units were intermediate. The superior performance of the phenolic encapsulated devices was attributed to the good match in the thermal coefficient of expansion between the phenolic material and the lead frame material.

is test degrading?

number of cycles?

There are two important questions about these test methods to which there are no definite answers: (1) is the test degrading to the wire bonds and (2) how many cycles constitutes a meaningful screening test? No general answers are available because they depend on the wire bonds and the associated device packages being tested, as indicated above, as well as on the

*F. Villella, Marshall Space Flight Center, Huntsville, Alabama 35812, private communication.

intended application of the device. With a better awareness of the factors that can affect the magnitude of the stresses to wire bonds, appropriate steps may be taken in the selection of constituent materials and in the bonding processes and procedures to minimize such stresses. These steps need to be taken at least in devices intended for use in such applications as satellite transmissions and other telemetry services where the device must sustain a great many on-off power cycles.

5.14. Electrical Tests

electrical tests

5.14.1. Introduction

limitations

A variety of electrical tests methods is in use but, aside from the measurement of the bond interface resistance, little has been reported about them in the literature. The use of an electrical test is attractive because of the possibility of automating it, but no test has yet been found to be sufficiently sensitive. Either the variable measured is insufficiently sensitive to the kinds of defects which may be present, or the variable of interest cannot be measured with sufficient sensitivity.

5.14.2. Bond Interface Resistance

interface resistance

The resistance of the bond interface is usually measured by a four-probe method. In this method a small, known current is conducted through the interface via one pair of contacts while the voltage across the interface is measured by a second pair of contacts.

sensitivity

The problem of insufficient sensitivity arises from the need to measure a small contact resistance in series with the larger resistances of the wire and metallization. Amlinger *et al.* [66A3] reported that the interface resistance measured was primarily a function of wire size and material and was of the order of 1.0 mΩ or less for gold or aluminum wire with diameter from 0.7 to 2 mils. The resistance that is usually quoted includes contributions from the wire and film and is of the order of 100 mΩ. An electrical resistance of 100 mΩ is equivalent to a length of about 1.5 mm of 1-mil diameter gold or aluminum wire. The electrical resistivity of both materials is about 3×10^{-6} Ω-cm [70C1].

mechanical integrity

The contact resistance has not been found to be a satisfactory measure to judge the quality of the wire bond. Amlinger *et al.* [66A2] found that such measurements did not give them insight into the mechanical strength of the wire bond. In a continuation of the work, Riben *et al.* [67R1] could not find any correlation between the contact resistance of the bond and the pull strength of the wire bond and therefore concluded that the resistance could not be used as a measure of mechanical integrity. However, because the pull

test is usually more a test of the wire rather than the bond adherence this conclusion is expected. A more meaningful evaluation of the method would be to determine the correlation which might exist between interface resistance and shear strength.

degradation detection

While Riben *et al.* [67R1] did not find the method capable of predicting which wire bonds would fail as a result of process variations, they did believe it was useful in detecting the electrical degradation due to exposure to elevated temperature of wire bonds with aluminum-gold interfaces.

electrical continuity

5.14.3. Electrical Continuity

The electrical continuity of the wire bond is usually tested by monitoring the voltage developed acros the wire bond by a small test current.

V-I characteristics

A convenient method is to use a transistor curve tracer. Any irregularities in the current-voltage curve or too great a voltage, as judged from previous experience, are used as grounds for rejecting the wire bond. Usually these criteria are symptoms of unsatisfactory electrical or physical continuity of the bond. A number of laboratories use some variation of this empirical test.

precautions

Some precautions related to the use of the method on gold-aluminum bonds have been suggested. Annular, micro-openings can form around gold ball bonds to aluminum films as a result of the Kirkendall effect soon after storage at as low a temperature as 125°C. To detect such defects may require the applied voltage to be limited to millivolts to avoid the possibility of arcing or other effects which would "heal" the micro-opening. Intermittent open-circuits can occur after such a "healing" event [71L1]. Cunningham* suggested that the application of even a tenth of a volt could heal such defects. The discharge of static charge has also been reported to heal micro-openings [66B5], hence it is advisable to make these measurements in a static-charge-free environment.

temperature effects

To detect intermittent electrical discontinuities the test is made at temperatures sufficiently above and below room temperature so that thermal expansion differences can perturb the wire bond. Browning *et al.* [66B5] reported intermittent continuity problems as the measurement temperature was changed. At one laboratory visited, the use of the test at an elevated temperature (125°C) was considered important. This was due to experience with bonds which passed the test at room temperature but exhibited intermittent electrical discontinuities at a higher temperature. At another laboratory, the use of the test at below room temperature was recommended. More recently, Brauer *et al.* [70B4] has recommended that in order to detect

*J. A. Cunningham, Texas Instruments, Stafford, Texas 77477, private communication.

intermittent bonds in plastic-encapsulated devices, electrical continuity tests should be made at both the maximum and minimum rated temperature. Haberer [71H2] has described this monitored thermal cycle test; its success in detecting such defects has prompted the recommendation of this test for use in MIL-STD-883.

monitored thermal cycle

Mann [66M1] has described a circuit for automatically detecting those wire bonds which exhibit too high a resistance. The circuit is designed to register a defect when less than 7 μA is conducted for an applied voltage of 0.3 V. Other voltage-current settings may be used to improve the detection of marginal bonds.

measurement circuit

Another approach to the continuity test, suggested by Kessler [70B2], is to use a high-current pulse of very short duration to detect poor bonds. This approach is based on experience with high-current pulsing of laser diodes. Weak bonds give an irregular current wave-shape pattern during the pulse or separate at the wire-die interface.

high-current test

noise

5.14.4. Noise Measurements

The generation of excess noise might be expected to result from the presence of defects such as (1) a mechanical contact rather than a metallurgical bond between the wire and the bonding surface, (2) micro-cracks at the heel of an ultrasonic bond, and (3) microvoids in the aluminum metallization at the periphery of a gold wire ball bond. This would be expected especially under a stress which would tend to move the wire bond and thereby alter the current path. However, no reports have been found which specifically deal with the use of noise measurements to detect weak wire bonds. Maki *et al.* [65M1] have described noise measurements to detect defective electronic components, but no mention was made about wire bonds.

no reports

US bond monitoring

5.15. Ultrasonic Bond Monitoring

5.15.1. Description

To identify weak ultrasonic bonds while they are being made, changes in the coupling between the wire and metal film during the ultrasonic bonding process are monitored. The monitoring has been attempted either by detecting the ultrasonic energy transmitted through the bond and into the substrate or by detecting the change in the loading of the ultrasonic driving system.

two methods

detecting transmitted US energy

Detecting the energy transmitted through the bond interface has been somewhat less successful than detecting changes in loading. The earliest attempt is one reported by Jones [62J1] who attached microphones to the supporting base so that spot and seam bonding of thin aluminum sheets

via microphones

could be monitored. He reported that the tensile shear strength of the bonds depended on the comparative ultrasonic energy transmitted through the bond. Therefore, if the driving frequency drifted from its design or resonant frequency a weaker bond would be made. The primary purpose of the monitor was thus to assure that the driving frequency was at resonance. Later Pruden and Schoenthaler [67P2] patented a method of determining the ultrasonic energy dissipated in the substrate by detecting temperature-induced changes in the electrical characteristics of the electrical component to which the wire bond is being made. In particular, they mentioned using the voltage-current characteristics of an adjacent p-n junction. They maintained that there exists a level of energy dissipation for which the bond quality will be a maximum. Bond quality was judged in terms of "maximum strength characteristics" and some minimum degree of bond deformation. It appears that this approach may have some practical disadvantages because the optimum level of energy dissipation measured, if it exists, would depend on such things as the relative location and uniformity of response of the adjacent temperature sensitive element monitored. In general it would not be possible to have such an element near each bonding area on the die. Furthermore, such a method would not be suitable for bonds made to the terminal.

via temperature-induced changes

via transducers

More recently Bellin *et al.* [69B7] have explored the use of transducers in the device holding fixture to measure the tangential forces during the bonding cycle. The tangential force, f, is related to the shear modulus, M, and the shear strain, S, of the aluminum wire, and the bonded area, A, by the following expression

$$f = MAS \text{ or } f = MAx/y,$$

where x is the lateral displacement of the top part of the wire with respect to the bottom, and y is the thickness of the deformed wire. If the maximum displacement of the wire is held constant by maintaining a constant driving power, the monitoring transducer system will measure a quantity that is proportional to the ratio of the effective bond area to the bond thickness. They proposed that this ratio is a function of bond adherence and could therefore be used as a measure to judge bond quality. Their work has not, however, progressed to a point where they were able to substantiate this proposal nor determine at what point in time a good metallurgical bond is achieved. One difficulty in interpreting the results of this technique may be related to recent observations by Leedy [70B3]. She reported that bonding can occur at one or more sites within the area of the wire-metallization interface in an irregular and non-reproducible way from bond to bond (see figure 5). These variations in the development and shape of bonded areas may affect the tangential force measured and hence make interpretation difficult. Also,

ultrasonic stress waves can affect the physical properties of metals [66L3] which implies that M will not be constant.

Several techniques have been explored for measuring the change in the loading of the ultrasonic system during bonding. These methods have followed one of two general approaches: monitoring the displacement of the transducer or bonding tool and monitoring the electrical parameters of the ultrasonic driving circuit.

detecting change in loading

The first report found of monitoring displacement is by Worlton and Walker [64W1] who described the use of a pickup cartridge in contact with the tool to monitor the tool displacement during the bonding cycle. They found that when the tool displacement amplitude decreased a good bond would be made while if this decrease was not seen a weak bond would be made. They also described a sensing circuit that stops the bonding cycle after a predetermined decrease in tool displacement is detected.

via pickup cartridge

A high-frequency microphone has been used to monitor the sound pressure from the tool and hence to measure qualitatively the tool displacement during bonding. The amplitude envelope of the sound pressure decreases as a good bond is established. A detailed description of the design and use of such a microphone system in addition to the use of a magnetic pickup is given by Harman and Kessler [71H1]. Quantitative measurements of the tool displacement have been made with laser interferometric techniques [70W1], [71B1], [71B4].

via microphone

Many commercial ultrasonic driving circuits incorporate feedback to minimize loading effects during loading. As a result, changes in the displacement amplitude of the transducer and tool are smaller. Therefore the measurement of tool displacement for bond monitoring is made less attractive because more sensitive detecting apparatus is required. An alternative first suggested by Worlton and Walker [64W1] is to monitor the electrical parameters of such driving circuits. Two commercial bonding machines incorporate such a bond monitoring approach.

via electronic feedback

Bonis* has described the use of small acceleration-detecting transducers attached to the transducer at various locations and to the top of the bonding tool. He also suggested that, despite the experimental difficulties, measurements of the acoustic standing wave ratio in the transducer could be used to monitor the impedance match at the bonding surface during the bonding cycle. Martin† has suggested that the various vibrational modes of the tool, as might be detected by measuring the displacement at the top of the tool with an attached accelerometer, might be relatable to the bond-making process, but studies by Harman [70B2] of tool oscillations with a

via acoustic SWR

*S. Bonis, Raytheon Company, Sudbury, Massachusetts 01776, private communication.

†C. T. Martin, ibid, private communication.

high-resolution capacitor microphone indicate that the displacement at the top of the tool does not necessarily relate to the displacement at the bonding-end of the tool.

via harmonic detection

Martin* identified the third-harmonic component of the tool vibration during bonding as a good indicator to use in bond monitoring. Later, in a computer simulation of the motion of a bonding tool, King [71K2] concluded that monitoring the higher harmonic content of the tool acceleration would be a more promising approach than monitoring either the acceleration magnitude (relatable to the tool displacement) or the acceleration phase. Harman [71B4], [71B5], [72B2] has recently described a mixer system for monitoring and studying harmonics of both oscillation amplitude and frequency during bonding as detected with a high-frequency microphone. Significant increases in the amplitude of the second and third harmonics during bonding were seen. These harmonics are best observed when the microphone is placed at a tool node.

discussion

5.15.2. Discussion

The attraction for bond monitoring is the possibility of identifying those isolated defective bonds that now go undetected and of detecting process drift much sooner than is now practical. However, the methods for monitoring the ultrasonic bonding process are still in an early stage of development. It remains to be seen just how useful any of them will be. Most of the methods explored so far depend on an interpretation of the shape of the tool displacement envelope or some other measure of loading as a function of time. This is not desirable for production line testing because of the additional time and judgment required for the interpretation.

needs development

sensitivity

Bonis† indicated that it was possible to identify strong bonds from the change of loading during the machine bonding cycle. Furthermore, it was possible to identify weak bonds which a visual inspection would pass; in these cases, the bond monitor indicated that either no coupling had occurred or that decoupling had occurred during the bonding cycle. It appears, however, that bond monitoring may not be sufficiently sensitive to detect some of the more subtle effects that may result in weak bonds. Under some conditions the monitor may indicate that a typical bond has been made, which a visual inspection will confirm, even though a weak bond has actually been made. This has been observed when, for example, the cleanliness of the bonding surface or the adherence of the metal film to the substrate was inadequate.§

*C. T. Martin, ibid, private communication.

†S. Bonis, ibid, private communication.

§H. K. Kessler and G. G. Harman, National Bureau of Standards, Washington, D. C. 20234, unpublished results.

Bond monitoring, even if it lives up to all expectations, cannot be considered as a complete screen for the wire bond. For example, such monitoring would not be expected to detect excessive weakening at the heel of the first bond due to post-bond wire bending in the process of shifting to the second bonding site, nor would it necessarily detect excessive deformation or a crack at the heel of a bond.

limitations

Even if monitoring is not installed as a production line test, it can be useful in process control measurement and bonding process studies. Also, it may be useful to apply the technique to other ultrasonic bonding schemes, such as face-down bonding [71H1].

process control

5.16. Correlation

correlation

Few comments have been made regarding the correlation between different test methods for evaluating a given type of wire bond. Generally, no substantiating experimental results are offered in the literature and the correlation or noncorrelation is dispensed with in a sentence or two. Those comments and results that have appeared in the literature are reviewed and evaluated below.

few reports

Generally, only a certain degree of correlation between pull and visual inspection test can be expected. Rather than correlating with each other so that one test might be substituted for another, the two methods tend to supplement each other. A visual inspection test will reject wire bonds which a subsequent pull test might find acceptable. Conversely, a visual inspection test will pass wire bonds which have acceptable wire deformations but have essentially no adherence. Furthermore, the visual inspection test is concerned with eliminating potential problems not directly related to pull strength, such as bond misplacement, excessive loop height, etc.

pull and visual inspection tests

Recent work by Kashiwabara *et al.* [69K1] have shown some interesting correlations between the lateral bond deformation and the pull strength of ultrasonic aluminum wire bonds. The pull strength was measured in a single-bond test where the direction of pull was 30 deg from the horizontal. They also found correlations between deformation and the ultrasonic bonding parameters of power, force, and time. All the bonds studied were made to aluminum films on an oxidized silicon substrate. They reported relative independence of the bond deformation on the aluminum film thickness.

bond deformation and pull strength

To assist in establishing more meaningful deformation criteria, if pull strength is to be the measure of quality, then more work of this kind is needed. For example, similar information about the deformation of bonds on the terminal and the effect of the condition of any metal film on the

terminal on the deformation would be extremely useful. It would also be useful to determine what effect changes in the tensile strength of the wire and the wire diameter would have on the correlation.

Bellin *et al.* [69B7] reported little correlation between the bond deformation and pull strength of ultrasonic aluminum wire bonds. However, the data shown to substantiate this claim, a plot of pull strength versus bond deformation, is similar to that shown by Kashiwabara *et al.* [69K1] except for more scatter in the points. It is not clear what causes this increased scatter, but it may be due to the mixing of results of bonds made with different bonding power and time settings.

pull, visual inspection, and electronic anvil tests

Plough *et al.* [69P1] mentioned that the results of pull tests with the use of a visual inspection test could be used to predict the ability of equivalent wire bonds to withstand the stresses imposed by an "electronic anvil test" (referred to in section 5.12 as the short-duration-stress pulse test).

pull and bond monitoring tests

Bellin *et al.* [69B7], in reporting some development work on a bond monitoring technique, found little or no correlation between their pull strength data and the outputs of their bond monitor. They questioned the use of pull strength data to judge completely the quality of the wire-to-chip bond and suggested that tests such as those using ultrasonic energy [69K4] be included in the evaluation of wire bonds. Their work only serves to point out that, potentially, a bond monitor will tend to indicate the quality of the bond itself while the pull test will provide an indication of the strength of, primarily, the heel of the bond unless very weak bonds are involved.

pull and centrifuge tests

Good correlation between single-bond pull (at 30 deg from the horizontal) and centrifuge (up to 60,000 g's) tests was claimed by Baker and Bryan [65B1]. It is implied that this correlation was found for both aluminum and gold wire bonds. Such correlation for aluminum wire would not be expected considering the negligible stress that an acceleration of even up to 60,000 g's would produce.

6. Summary

summary

Two critical areas for reliability improvement of wire bonds are manufacturing process control and testing and evaluation methods. Despite the variety of test methods used, no one or combination of methods has been devised to cull out all wire bonds that will fail. In addition, the fabrication processes are either not sufficiently well understood or are not sufficiently well controlled or both to be able to make the same wire bond *every time.*

process control

test methods

The essential features of the thermocompression and ultrasonic bonding processes, the fabrication procedures, the bonding equipment, and the characteristics of the constituent materials of the wire bond pertinent to high reliability are discussed in section 4. Also in section 4 is a review of the degradation effects of the interaction of gold and aluminum in wire bonds at elevated temperatures. It is emphasized that a large number of variables must be considered and controlled when making wire bonds and that there is relative ignorance of the quantitative (and in some cases qualitative) effects that these variables have on the reliability of the wire bonds produced.

fabrication variables

The methods used to test and evaluate wire bonds are discussed in section 5. In general there is little in the published literature that can be used to evaluate the methods in terms of (1) the criteria to establish the reliability or quality of the wire bonds and (2) the effects of variations in the test variables on the test results. An additional widespread problem in the literature is the underspecification of both the methods used and the wire bonds tested. Brief summaries of the comments made in section 5 about the various methods are given in the following paragraphs.

test criteria and variables

The most widely used nondestructive (and nondegrading) test method for wire bonds is the visual inspection test. It usually contains an extensive list of reject criteria. The method can be used to detect relatively gross defects but its success in detecting the more subtle defects is mixed.

visual inspection

The pull test is the most widely used destructive test. The method can be fast and easy to perform and it provides a number, the pull strength, for use as a quality measure. However, the temptation is to use only this number without specifying other data needed to interpret the pull strength. Hence pull-test data is often of limited value. A nondestructive form of the pull test is also used. Skepticism that the method is actually nondegrading and the need for more detailed reports of its effectiveness has hindered wide use of the method.

pull test

The centrifuge test is also a widely used test. It is considered by many to be useful for wire bonds with gold wire but not for those with

centrifuge test

aluminum wire because of the lower density of aluminum. Even for gold wire it may be either inconvenient or damaging to other components of the device if acceleration levels at which a significant stress can be imposed on the wire bond are attained.

air blast test

The air blast test is a relatively little used nondestructive test. An air jet is directed at the wire bonds on the device to stress them mechanically. An often expressed reservation about the method is the difficulty of quantifying the stress imposed on the wire bond. Consequently the test is usually performed at a conservatively low air velocity to cull out only the weakest wire bonds.

push test

The recently suggested push test, in which a probe applies a deflecting force to the apex of the wire span, appears to offer, in most cases, greater control over the applied stress but is slower because each wire bond is tested individually. The push test method offers the potential advantage over the nondestructive pull test in that the shape of the wire span is not altered.

mechanical shock test

The mechanical shock test is generally regarded as being of marginal value because of the small peak deceleration usually used in the test. One limitation to increasing the stress is that the device package may be damaged; providing the special jigging required to reduce package damage is usually inconvenient.

short-duration stress pulse test

The short-duration stress pulse test is in limited use. The tensile stresses generated by the absorption of pulses of high-energy electrons can reach spall thresholds in the wire bond.

variable frequency and vibration tests

The variable frequency vibration and the vibration fatigue tests are of marginal value, at best, because of the small stress imposed. The lowest resonant frequency of most wire bonds is much higher than the maximum excitation frequency and the peak acceleration produces an essentially insignificant stress.

ultrasonic stress

The ultrasonic stress method involving the use of focused ultrasonic power to stress wire bonds has been explored empirically. Significant stress levels can be reached with this method to cause failure in even strong wire bonds. A better understanding of the nature of the stress imposed and how its magnitude is affected by the test variables is needed before the method can be evaluated.

temperature cycling and thermal shock

Temperature cycling and thermal shock tests are widely used but there has been disagreement about the effectiveness of these methods. The stress and hence the effectiveness of the tests is dependent on the differences in the thermal coefficients-of-expansion of the constituent parts of the device and the shape of the wire span.

electrical tests

A variety of electrical test methods is in use to evaluate the electrical connection at and near the bond interface between the wire and the bonding surface. The use of an electrical test is attractive because of the

possibility of automating the test, but no test is sufficiently sensitive to go much beyond detection of open circuits. Either the property measured is insufficiently sensitive to the kinds of defects which may be present or the property cannot be measured with sufficient sensitivity.

shear test

The shear test is used to obtain a measure of the adhesion of gold ball bonds. The method is not widely used and apparently suffers from poor precision.

ultrasonic bond monitoring

Bond monitoring methods are attractive for the case of ultrasonic bonding because they offer the possibility of checking each bond as it is made to identify isolated defective bonds that otherwise could go undetected and of detecting unintentional variations in the fabrication process much sooner than is now practical. Various techniques for bond monitoring are under consideration but all are in an early stage of development and require much more work before adequate evaluations can be made.

7. APPENDIXES

7.1. Appendix A. Estimate of Lowest Resonant Frequency of Wire Bonds

To obtain an estimate for the lowest resonant frequency of a wire bond with a given bond separation, assume that the wire loop describes a circular arc. That is, the wire loop may approximate any circular arc from the extreme of a straight wire to that of a semicircular loop between the two bond sites. The three frequency modes to be considered are extensional, non-extensional (node at mid-span), and lateral (perpendicular to the plane of the wire loop). These modes are sketched in figure A1 for the case where the wire describes a semicircular arc. Approximate values of the resonant frequencies of the lowest extensional and non-extensional modes of vibration [28D1] and the lowest lateral mode of vibration [34B1] have been calculated for clamped-end connections. The general expression for the resonant frequency, f_{oi}, is given by,

$$f_{oi} = C_i \sqrt{\frac{EI}{\mu d^4}} \qquad \text{(A.1)}$$

where E = modulus of elasticity (dynes/cm^2),

I = moment of inertia of area (cm^4),

μ = mass per unit length of wire (g/cm),

d = separation of bonds (cm), and

C_i = frequency coefficient of the mode.

The frequency coefficients for the three modes, C_1, C_2, and C_3, are all dependent on the subtending angle,* Θ. In addition, C_1 also depends on the ratio of the bending to torsional stiffness, k, and C_2 also depends on the value of $R = (d/r)\,[(d/4h) + (h/d)]$, where r is the wire radius. The variations of C_i for each of the three modes as a function of the subtending angle and the ratio of bond separation to loop height, d/h, are shown in figure A1. The values of C_1 are for the case where the ratio of the bending to torsional stiffness, k, is equal to two.† The dependence of C_2 is given for two values of R. As may be seen from figure A1 and equation (A.1), the lateral mode of vibration will have a significantly lower resonant frequency than either of the other two modes, except for small subtending angles where the resonant frequencies of the lateral and extensional modes approach each other.

---

*The product of the subtending angle and the radius of curvature of the wire arc is equal to the wire length.

†$k = EI/RJ$ for a circular cross-section, where E and R are, respectively, the modulus of elasticity and of rigidity, and I and J are, respectively, the moment and the polar moment of inertia of area. The value of $k = 2$ was taken as a convenient upper-bound. This was done with the recognition that C_1 is not a sensitive function of k within the range of values reported for aluminum and gold [68S3]. The use of a value of k = 1.[illegible], which would be a lower bound for the values of k reported, would increase the value of C_1 by less than 3 percent.

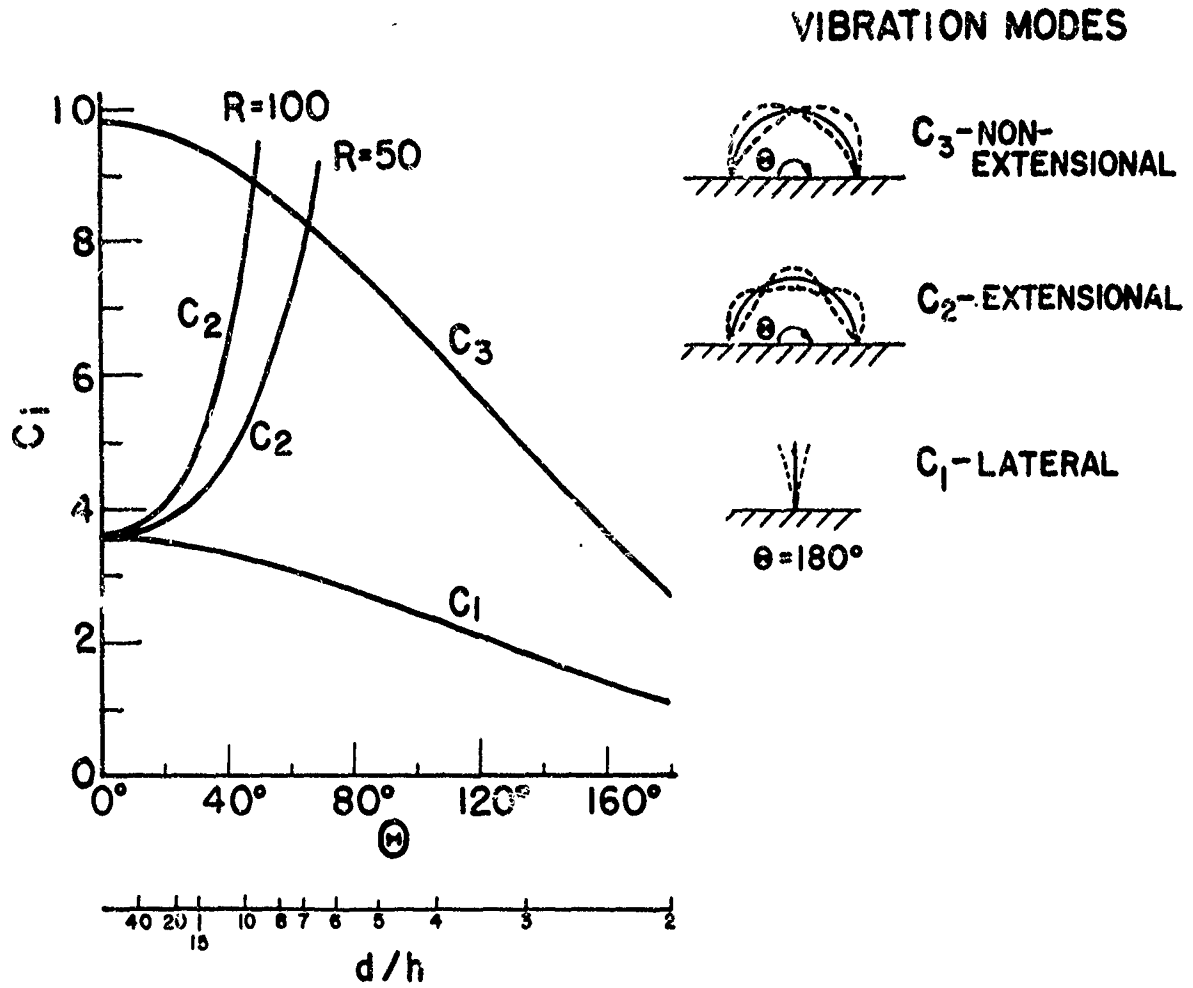

Figure A1. Variation of the frequency coefficients, C_i, with subtending angle, Θ, and ratio of bond separation to maximum wire span height, d/h, for each of three vibration modes, identified by the sketched modes for Θ = 180 deg. The coefficient C_2 depends on the value of $R = (d/r)\,[(d/4h) + (h/d)]$, where r is the wire radius. The dependence of C_2 on Θ is given for two values of R.

The dependence on bond separation of the resonant frequency* for the lateral vibration mode is shown in figure A2 for 1-mil diameter gold and aluminum wire bonds with a circular wire loop for three different values for d/h: 2, 5, and infinity. For d/h = 2, the wire loop is a semicircle, a highly unlikely configuration. It is expected that most wire loops will lie between the arc where d/h = 5 and a straight wire (d/h infinite). These calculations are based on the assumption that the wire ends are clamped to the bond sites. In real wire bonds the condition of the stiffness of the wire connection to the bonding site should be between that for a clamped and for a hinged, free-roll connection. Hence for more conservative lower bounds for the resonant frequency of wire bonds, the frequency coefficient C_1, and consequently all curves in figure A1, may be lowered by about 25 percent to allow for a less stiff connection.

*f_{oi} was calculated using the values for E of 7.0×10^{11} dynes/cm^2 and 7.8×10^{11} dynes/cm^2 for aluminum and gold, respectively.

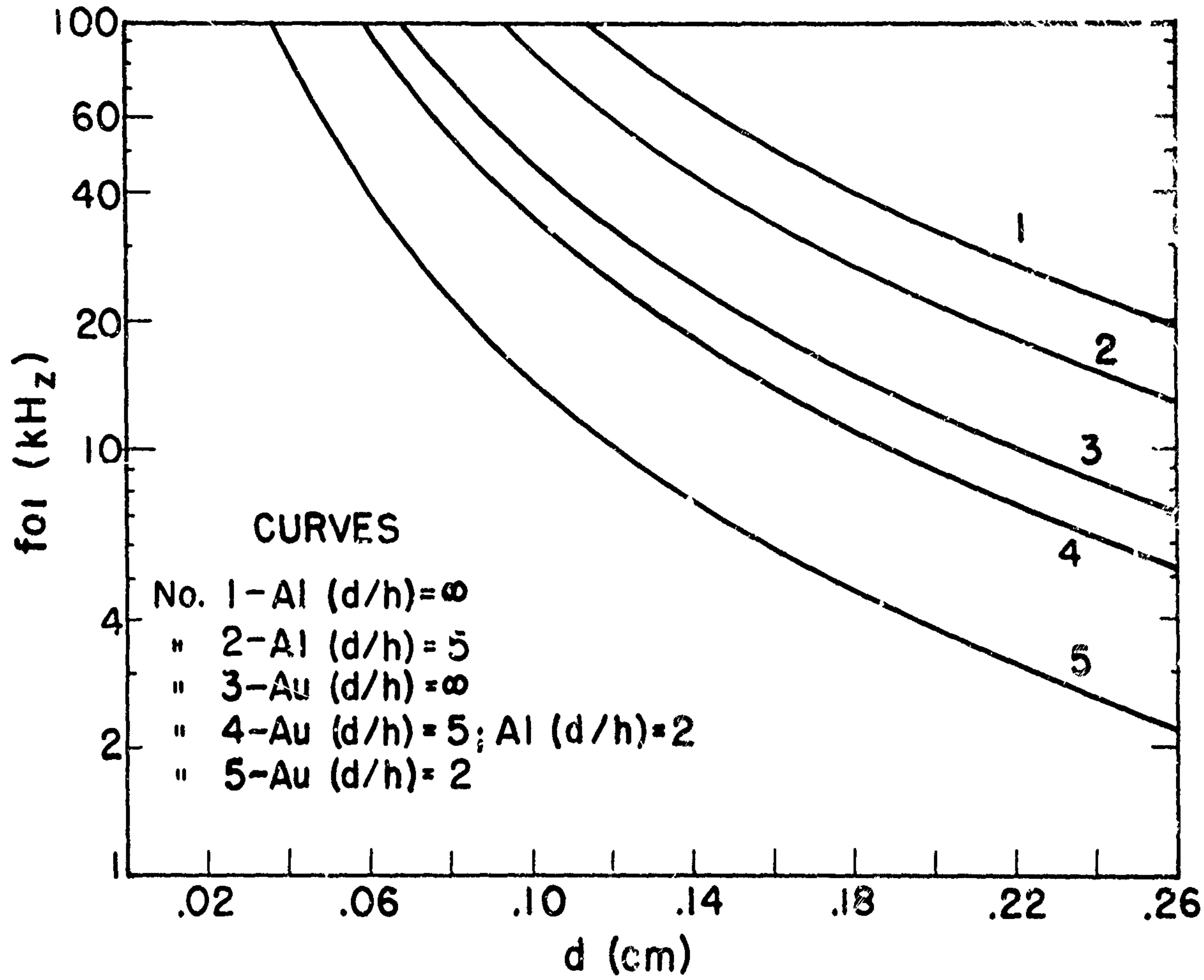

Figure A2. Dependence of the resonant frequency, f_{01}, on bond separation, d, for the lateral mode of vibration for 1-mil diameter gold and aluminum wire bonds with circular shaped wire spans having the ratios of d/h equal to 2 (semicircular), 5, and infinity (straight wire). The height of the span at its apex is h.

7.2. Appendix B. Expression Relating Four Measures for Pull Rate

Four measures of pull rate in the pull test are mentioned in section 5.3.2: rate of straining, R_n; rate of stressing, R_s; elapsed time for completing part or all of the test, τ; and speed of the moving head during the test, ν. These measures are related below for the simple case of the wire bond pulled at mid-span and in a direction perpendicular to the bonding surface as shown in figure B1.

$$\tau \stackrel{\sim}{\sim} \frac{\varepsilon}{R_n} \stackrel{\sim}{\sim} \frac{\varepsilon \ell^2}{\nu h^2} \stackrel{\sim}{\sim} \frac{\varepsilon E}{R_s} \stackrel{\sim}{\sim} \frac{\ell F}{2AR_s h} \qquad (B.1)$$

where R_n = rate of straining, per unit gauge length (s^{-1}),

R_s = rate of stressing, per unit area ($N\ cm^{-2}\ s^{-1}$),

τ = elapsed time in pull test (s),

ν = speed of pull, per unit gauge length (s^{-1}),

ε = wire elongation,

ℓ = wire distance from bond to mid-span,

h = wire loop height,

E = Young's modulus of elasticity ($N\ cm^{-2}$),* and

F = pull strength of wire bond (N).

The above relations may be obtained as follows: First, $R_n = (1/\ell)\ (d\ell/dt) \stackrel{\sim}{\sim} (1/\ell)\ (\Delta\ell/\Delta t) = \varepsilon/\tau$, where t is time; therefore $\tau \stackrel{\sim}{\sim} \varepsilon/R_n$. Second, $\nu = (1/h)\ (dh/dt) \stackrel{\sim}{\sim} (1/h)\ (\Delta h/\Delta t)$; but $dh = (\ell/h)d\ell$ and $\Delta h \stackrel{\sim}{\sim} (\ell/h)\Delta\ell$, so $\nu \stackrel{\sim}{\sim} (\ell/h^2)$ or $(\Delta\ell/\Delta t) \stackrel{\sim}{\sim} \nu h^2/\ell$. As already seen, $\tau = \varepsilon\ell/(\Delta\ell/\Delta t)$; therefore $\tau \stackrel{\sim}{\sim} \varepsilon\ell^2/\nu h^2$. Third, $R_n = R_s/E$. Hence, from the first relation, $\tau \stackrel{\sim}{\sim} \varepsilon E/R_s$. Fourth, $R_s = (1/A)\ (dF_w/dt)$, where F_w is the tensile force in the wire and A is the cross-sectional area. But, $F_w = F\ell/2h$. Therefore $R_s \stackrel{\sim}{\sim} (\ell/2Ah)\ (\Delta F/\Delta t) \stackrel{\sim}{\sim} (\ell/2Ah)\ (F/\tau)$, or $\tau \stackrel{\sim}{\sim} \ell F/2AhR_s$.

*For aluminum and gold, E is, respectively, about $7.0 \times 10^6\ N/cm^2$ and $7.8 \times 10^6\ N/cm^2$.

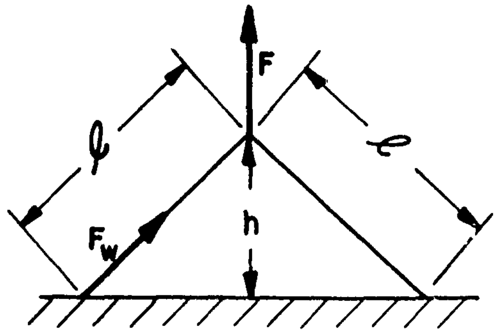

Figure B1. Illustration of double-bond pull test.

8. REFERENCES

8.1. Introduction

identification code

Each citation has been given an identification code* which consists of a sequence of two digits, a letter, and another digit. The first two digits indicate the year of publication and the letter is the initial of the first author's surname. The last digit is used to distinguish those papers which would otherwise have the same code. No rule was used in the assignment of the last digit.

ordering

The papers in the bibliography are arranged according to their codes. The codes are grouped first by year, then in alphabetical order by letter, and then in numerical order by the last digit.

availability

Some citations are followed by notes which refer to additional information intended to assist in obtaining the referenced work. Reports available from the National Technical Information Service (NTIS), Sills Building, 5285 Port Royal Road, Springfield, Virginia 22151, are followed by a number preceded by the letters AD or PB, or the letter N. This is the NTIS Accession number which should be used when ordering.

addresses

A number of other citations, generally to conference papers, are followed by a number either in brackets or parentheses. The number refers to one of the addresses listed in section 8.3. If the number is in brackets the address listed is one to which an order may be placed for the paper or the conference proceedings. If the number is in parentheses the address is that of the first author's place of work at the time the paper was published.

guidance

Some citations are also followed by guidance in brackets. For example, reference may be made to the pages in the paper that are relevant to the subject.

location in text

All citations are followed by the page number(s) in the text where the paper is cited. These page numbers are in braces.

abbreviations

The journal or conference abbreviations generally follow those of the Chemical Abstracts. In order to minimize any possible confusion, those journals abbreviated are listed in alphabetical order by their abbreviations in section 8.4. Additional abbreviations are included which are used in citations to some conference meetings.

*The identification codes used are taken from a comprehensive bibliography on wire bonds [72S1] for convenience in perusal of both the bibliography and this paper.

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(36) RCA, Somerville, New Jersey 08876.

(37) Motorola Inc., Phoenix, Arizona 85008.

(38) Delco Electronics Division, General Motors Corp., Milwaukee, Wisconsin.

(39) NASA Marshall Flight Center, Huntsville, Alabama 35812.

8.4. Abbreviations

AIME - American Institute of Mining, Metallurgical and Petroleum Engineers

ASME - American Society of Mechanical Engineers

ASTM - American Society for Testing and Materials

ASTME - American Society of Tool and Manufacturing Engineers

Appl. Phys. Lett. - Applied Physics Letters

Bell Lab. Rec. - Bell Laboratories Record

Brit. Commun. Electron. - British Communication and Electronics

Brit. J. Appl. Phys. - British Journal of Applied Physics

Circuits Mfg. - Circuits Manufacturing

Conf. - Conference

EDN - (formerly Electrical Design News)

EE - (now, The Electronic Engineer; formerly, Electronic Industries)

Electron. Packag. Prod. - Electronic Packaging and Production

Electron. Prod. - Electronic Products Magazine

Electronic Engineer - The Electronic Engineer (formerly EE, formerly Electronic Industries)

Electron. Lett. - Electronics Letters

Electro-technol. - Electro-technology (New York)

Eval. Eng. - Evaluation Engineering

IEEE - Institute of Electrical and Electronics Engineers (formerly IRE)

IEEE Intern. Conv. Record - IEEE International Convention Record (formerly IRE ...)

IEEE Trans. Electron Devices - IEEE Transactions on Electron Devices (formerly IRE ...)

IEEE Trans. Nucl. Sci. - IEEE Transactions on Nuclear Science

IEEE Trans. Pts. Materials Packaging - IEEE Transactions on Parts, Materials, and Packaging

IEEE Trans. Sonics Ultrason. - IEEE Transactions on Sonics and Ultrasonics

Int. - International

IEC - International Electrotechnical Commission

IRE - Institute of Radio Engineers

IRE Intern. Conv. Record - IRE International Convention Record

IRE Trans. Electron Devices - IRE Transactions on Electron Devices

J. Appl. Phys. - Journal of Applied Physics

J. Electrochem. Soc. - Journal of the Electrochemical Society

J. Sci. Instrum. - Journal of Scientific Instruments

Mater. Eval. - Materials Evaluation

Mater. Res. Std. - Materials Research and Standards

Metals Eng. Quart. - Metals Engineering Quarterly

Mfg. - Manufacturing

Nat. Electron. Conf. - National Electronics Conference

NEPCON - National Electronic Packaging and Production Conference

Philips Tech. Rev. - Philips Technical Review

Proc. IEEE - Proceedings of the Institute of Electrical and Electronics Engineers

Prod. Eng. - Product Engineering

Rev. Sci. Instr. - The Review of Scientific Instruments

Rev. Elec. Commun. Lab. - Review of the Electrical Communications Laboratory. Tokyo. (Denki Tsushin Kenkyujo)

SAE - Society of Automotive Engineers

Semicond. Prod. - Semiconductor Products

Semicond. Prod. Solid State Technol. - Semiconductor Products and Solid State Technology

Soc. - Society

Solid State Electron. - Solid State Electronics

Solid State Technol. - Solid State Technology

Symp. - Symposium

Technol. - Technology

Trans. Met. Soc. AIME - Transactions of the Metallurgical Society of the AIME

Welding J. - Welding Journal

WESCON - Western Electric Show and Convention

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